A STUDY OF THE SURFACE HEAT BUDGET OF THE INDIAN OCEAN

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S T A T E M E N T

As required under the ordinance No. O.413, I state that the present thesis entitled " A STUDY OF THE SURFACE HEAT BUDGET OF THE INDIAN OCEAN " is my original contribution and that the same has not been submitted for any degree of this or any other university on any previous occasion.

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CHAPTER I

INTRODUCTION

A fundamental consideration in global energetics is the relative roles of the tropical atmosphere and ocean in the poleward redistribution of the net radiative heat surplus received by the tropics (Hastenrath and Lamb, 1980). The radiative, momentum and heat fluxes of the tropical oceans at the air-sea interface play a vital role in the global atmospheric and oceanic circulation and their heat budgets.

In recent years, numerous investigators are looking into the vital role of the heat budget of the tropical oceanic areas in the formation of weather and climatic variations over different parts of the globe. Among the world oceans, the Indian Ocean shows unique characterstics because of the semiannual pheneomena known as monsoons (southwest and northeast). Numerous investigators (U.S.Weather Bureau, 1938; Koninklijk Nederlands Meteorogisch Institute, 1952; Ramage et al 1972) have prepared the marine climatic atlases of the Indian Ocean region. But their data coverage in general is limited and only a few surface meteorological parameters have been presented in them. Hastenrath and Lamb (1979a & 1979b) have presented a detailed climatic atlas of the tropical Indian Ocean utilizing the data for the period 1911-1970 with one degree grid spatial resolution. The large scale experiments like the International Indian Ocean Expedition (IIOE), Indo-Soviet Monsoon Experiment (ISMEX-73), MONSOON-77 and MONEX-79 have been able to generate lots of data over most of the tropical Indian Ocean areas. But these data sets are also quite inadequate in both temporal and spatial scales needed for understanding/predicting the monsoon onset problem, the active and break monsoon conditions over the Indian subcontinent and the source of moisture for the summer monsoon rainfall.

Studies by Rao et al., (1977,1981) have shown that the north Indian Ocean heat budget components vary drastically during the onset and break-monsoon conditions especially over the north Indian Ocean. Ramanadham et al.,(1981) using the data collected during MONSOON-77 have shown that there are significant differences in the heat budget components during the different monsoon periods.

Ramesh Babu and Sastry (1984) using the data sets of MONSOON-1977 and MONEX-1979 programmes studied the summer cooling in the east central Arabian Sea. Their study revealed that the downward transfer of heat due to mixing of warm surface and cold subsurface waters was associated with the deepening of the current shear zone and this is the predominant processes for the observed cooling in this region. The rate of cooling was found to be greatest immediately after the onset of strong monsoon winds and the development of anticyclonic wind stress curl, which gives rise to a southerly current off the west coast of India. The downward flux of heat was also found to vary in the study area with generally higher values in the western regions where the growth of surface layer is maximum.

Ramesh Babu et al ., (1989) using the data obtained at the 3 hourly interval during the summer monsoon days (25-31 July, 1977) had examined the time history of the surface heat balance parameters of the central equatorial Indian Ocean (2^{o}N to 2^{o}S, 76^{o} to 80^{o}E) on a short time scale. They have found that, the heat content of the upper 200 m water column at an average rate 900 Wm^{-2} can be mainly attributed to the oceanic interior (advection) processes. A simple heat budget model was adopted to compute the advection rates whose orders were found comparable with those of the observed currents near the study area.

In recent years, considerable attention has been paid to the relationships between SST distribution over the Indian Ocean and the monsoon activity over India and adjoining areas (Ellis 1952; Saha 1970; Shukla 1975; Washington et al 1977; Pisharoty 1981; Mishra 1981; Joseph 1981; Joseph and Pillai 1984). In most of the above mentioned studies the attempt was to correlate between the SST anomalies in the Arabian Sea and the monsoon rainfall.

The results obtained from the above studies differ because of the different methodologies, study periods and areas used.

Shukla (1975) using a global primitive equation (PE) numerical model simulated the influence of a cold SST anomaly in the Arabian Sea . He attributed the following effects to colder water:

(1) reduced evaporation over the Arabian Sea,
(2) slight increase in sea level atmospheric pressure downwind of the anomaly,
(3) weakened cross-equatorial surface flow from 30 to 70^{o}E with lower moisture flux, and
(4) reduced precipitation over India.

Washington et al., (1977) used the same cold SST anomaly but with a different General Circulation Model (GCM), found lower precipitation only over the anomaly, enhanced rainfall rates farther south and east, and no change in the rainfall over the Indian subcontinent.

Druyan et al.,(1983) conducted GCM experiments, using the same cold SST anomaly used by Washington et al.(1977) and Shukla (1975) (i.e., SST pattern 1-3^{o}C below the climatological mean over the western Arabian Sea area) and using the Goddard Institute for Space Studies (GISS) version 1 of the GCM, and by making the SST sensitive to atmospheric forcing. The results obtained by him differed from the previous studies of Washington et al.(1977) and Shukla (1975) in that the model was able to reproduce the increase in precipitation over the Indian subcontinent, which can be attributed to the release of moisture obtained upwind the anomaly induced thermal stability.

Joseph and Pillai (1984) have studied the relationship between SST values over three selected regions (two in the Arabian Sea and one in Bay of Bengal) with the monsoon rainfall over India, utilizing the data collected for the period 1961 to 1973. Their study showed that the SST exhibited a prominent three year periodicity in addition to the annual variation. Correlations between SST of premonsoon months and monsoon rainfall showed positive correlation but was not statistically significant. The monsoon rainfall was significantly and negatively correlated with the post monsoon SST of the selected areas.

The role of SST on the Indian summer monsoon rainfall has been a controversial topic for years (Ramage, 1971; Saha, 1974; Shukla and Misra, 1977; Weare, 1979; Ranjith Singh, 1980; Anjaneyulu, 1980; Ramesh Kumar et al., 1986a, 1986b; Kusuma Rao and Goswami, 1988). Ramage (1971) suggested that the summer cooling of the Arabian Sea (AS), has significantly contributed to the sea level pressure variations over the oceanic regions. Recent studies of Ramesh Kumar and Sadhuram (1988), Vinayachandran et al., (1989) and Vinayachandran and Ramesh Kumar (1989) have suggested that this pressure variations in turn affect the monsoon moisture flow into the Indian subcontinent.

Saha (1974) on the other hand has suggested that the higher SST's in the Indian Ocean region would to lead to higher evaporation and this in turn will release more moisture into the atmosphere which will result in good monsoon.

Shukla and Misra (1977) using the data collected for the period 1901-1960, has found that the SST in a small region near 10^{o}N and 65^{o}E was weakly and positively correlated with the monsoon rainfall over various meteorological subdivisions, in India.

Weare (1979) found that the warmer AS or Indian Ocean is weakly associated with the decreased rainfall over most of the meteorological subdivisions by performing an empirical orthogonal functional analysis on the Indian Ocean data for the period 1949-1972.

Ranjith Singh (1980) found that the zones of the warmest SST during the premonsoon months of April and May are found to be at the northern latitudes in good monsoon years (1961, 1964) than in bad monsoon years (1965, 1966). Anjaneyulu (1980) using a composite of good and bad monsoon seasons has found that the negative anomalies of SST during August over the western AS are associated with subsequent good monsoon and vice versa.

Kusuma Rao and Goswami (1988) using the data for the period (1900 - 1979) have shown that the SST over two 5^{o} square boxes in the southeastern AS during the premonsoon months correlates most strongly and significantly with the monsoon rainfall. They further showed that except over one in the Bay of Bengal (between 10^{o} and 15^{o}N, 90^{o}-95^{o}E) the June to August SST over most of north Indian Ocean does not significantly correlate with monsoon rainfall. The post monsoon SST correlates negatively over most of the oceanic regions and spatial homogenity of the correlation field was high, with the highest significant correlations occuring in the western and northern Arabian Sea.

Pearce and Mohanty (1984) have carried out a detailed analysis of the moisture and mean tropospheric enthalpy based on the FGGE data for the months May and June, 1979 for the onset of the Asian summer monsoon. Their study revealed that the onset consists of two main phases 1) a moisture build-up over the Arabian Sea during which synoptic and mesoscale transient disturbances develop; the relationship of this build-up with the planetary wave activity is discussed. This is followed by 2) a rapid intensification of Arabian Sea winds and sustained increase in latent heat release, essentially a large scale feedback process.

Shetye (1986) using the monthly mean surface heat fluxes and the surface advective field modelled the seasonal cycle of the Arabian Sea sea surface temperature variablilty. His study showed that the surface and momentum fluxes alone could simulate the model throughout the year except for the southwest monsoon months. Addition of the horizontal and vertical advection terms improved the model for the monsoon period.

Inspite of these studies, considerable uncertainty still exists as to the exact nature of the relationship between SST patterns and monsoon activity. These theoretical and empirical models need verification by extensive testing with observed data. Conventional ship observations over the Indian Ocean are sparse, and as such, not ideally suited for the above purpose. It is now possible to get SST data on a routine basis, through satellites. Though uncertainties still exist as to the accuracies of this data, especially for tropical areas, it has the advantages of large area coverage and real time accessibility, which are important attributes from the prediction point of view.

Mishra (1981) studied SST variability over the North Indian Ocean during the southwest monsoon season for the years 1977, 1978 and 1979, using the satellite derived SST data. The study revealed that the beginning of cooling of surface waters over the Arabian Sea is associated with the advance of the southwest monsoon, and that the formation of the Somali and Monsoon currents and spreading of cold upwelled waters over the Arabian Sea are more pronounced in good monsoon years.

Ramesh Kumar et al., (1986a) using the satellite derived SST data over the Indian Ocean during the premonsoon and monsoon period, for the years 1979 and 1983 have discussed the various hypotheses regarding the ocean-atmosphere interaction and its possible effect on monsoon rainfall over India.

Simon and Desai (1986) have shown that the evaporation estimates can be made over the oceanic areas using the operational meteorological satellites data. Their study indicated that the latent heat flux shows a marked peak around onset time between 50^{o}-55^{o}E in the equatorial Indian Ocean belt and the flux was found to decrease from 200 Wm^{-2} to 30 Wm^{-2} after the onset period.

The origin of source of moisture which produces intense rainfall over the Indian subcontinent, is not yet clearly understood. The relative roles of Arabian Sea and the cross-equatorial flow are still debated (Pisharoty, 1965; Saha and Bavadekar, 1973; Ghosh et al., 1978; Cadet and Reverdin, 1981; Howland and Sikdar, 1983; Murakami et al.,1984; Cadet and Greco, 1987; Sadhuram and Ramesh Kumar, 1988; Ramesh Kumar and Sastry, 1989).

Pisharoty using the I.I.O.E data concluded that the role of the cross-equatorial flux towards the transport across the west coast of India is minimal and that the Arabian Sea provides most of the moisture needed for the summer monsoon rainfall. Saha and Bavadekar (1973) using the same data but with additional upper air observations found that the cross-equatorial flux contributes to about 60-80% of the moisture transported across the west coast of India. Cadet and Reverdin (1981) using 1975 summer monsoon water vapour transport data found that the cross-equatorial flux was more important than the Arabian sea moisture. Howland and Sikdar (1983) performed a detailed study during the premonsoon and active and weak phases of the monsoon and they observed dramatic changes in the kinematic and moisture fields during the different phases.

Shukla and Mooley (1987) have examined about 46 years of data (1939-1984) to study the synoptic and statistical relationship between the summer monsoon rainfall over India, the Southern Oscillation and the mid tropospheric circulation over India, from a prediction point of view. They have developed an emipirical formula to predict the rainfall from the above parameters. Verification of the predictions on independent data showed that the root mean square for the predicted rainfall is 36 mm, which is less than half of the standard deviation (82 mm) and only about 4% of the mean rainfall (857 mm).

Elliott and Angell (1987) have tried relationship between the Indian monsoon rainfall, the Southern Oscillation and the hemispheric air and sea temperature for the period between 1884 to 1984. The study has revealed that the monsoon rainfall anticipates the Southern Oscillation indices and the individual station pressure deviations. Monsoon rainfall over India is also negatively correlated with sea surface temperature in the eastern equatorial pacific one to two seasons later. The correlations suggest that above average monsoon rainfall is associated with below average southern hemisphere temperatures two to three seasons later, whereas above average northern hemisphere winter temperatures - particularly continental temperatures - anticipate above average rainfall. A strong negative correlation (-0.64) between the seasonal change in Darwin's pressure deviation from December-February to March-May and the monsoon rainfall is found for the period 1947-1984, but only weakly in the period before 1947.

Numerous investigators both meteorologists and oceanographeres have been trying to improve the long range forecasting of the Indian monsoon rainfall, as the summer monsoon is of vital importance to the economy of the country, as about 70 to 90% of the annual rainfall for the various meteorological subdivisions is received during this period (June to September). An exact idea about the role of the Indian Ocean surface heat budget on the summer monsoon has not yet emerged, even though numerous authors have given contradicting theories and hypothesis. Varadachari et al., (1987) have given a critical review of the role of the Indian Ocean in relation to the Indian summer monsoon rainfall.

The objective of the present study is to analyse the surface heat budget of the tropical Indian Ocean using the unpublished data set of Bunker for the period 1948-1972, and to find whether any relationship exists between these air-sea fluxes and the monsoonal circulation, the SST or any other oceanic parameter that can be used for predicting the onset and the monsoon rainfall over the Indian sub-continent and the source of moisture for the summer monsoon rainfall.

Chapter 2 describes the data used and the various methodologies used for computing the radiative, momentum and heat fluxes and the meridional heat transports and also mentions the various errors involved while computing the above fluxes.

Chapter 3, presents the mean seasonal and annual fluxes over the tropical Indian Ocean along with the mean annual meridional heat transport.

The air-sea interaction processes during several contrasting monsoon seasons are presented in chapter 4, utilizing the data from a variety of sources (satellite derived SST data, IDWR data and Bunker data).

In chapter 5 an attempt is made to identify the various causative mechanisms of the sea surface temperature anomalies, their amplitudes and duration periods in the Arabian Sea.

Chapter 6 gives the relationship between the evaporation over Arabian Sea, Bay of Bengal and southern Indian Ocean; SST over different study areas; position of the 500 mb ridge and Southern Oscillation with the monsoon rainfall over India.

The conclusions of the present study are summarised in chapter 7 of the thesis.

CHAPTER II

DATA AND METHODOLOGY

The data needed for the present study have been extracted from the unpublished data set of Bunker for the Indian Ocean. It consists of monthly values of surface meteorological parameters like sea surface temperature (SST), air temperature, mixing ratio, air-sea temperature difference, cloud cover, wind speed, sea level pressure , number of observations etc., for the north and south Indian Oceans calculated from the ship/marine weather reports for the period January 1948 to December 1972.

This data set contains data pertaining to 78 Marsden squares (10^{o} X 10^{o} square grids) out of which we have chosen only those squares which lie between latitudes 30^{o}N and 30^{o}S and longitudes 40^{o}E and 100^{o}E. Figure 1a presens the study area with the Marsden square numbers used in the present study. Figure 1b gives the study areas used for computing the evaporation rates over the Arabian Sea (Area A), southern hemisphere (Area B) and Bay of Bengal (Area C).

Figure 2a gives the total number of observations used in the present study for each Marsden Square (MSQ). The numbers are greatest in squares which encompass traditional shipping routes, whereas the numbers are smallest in the southeast part of the study area. Figure 2b gives the number of months for which data are available for each MSQ out of a possible 300 months; here again the numbers are larger over the northern Indian Ocean than over the south Indian Ocean. Figure 3 gives the mean monthwise data density for the bad (open) and good (circled) composites for the study area over the tropical Indian Ocean.

The quality of the observations have been thoroughly checked in this study using the criteria followed by Joseph (1983) and is as follows:

(a) SST observations in the range $15^{\circ}C$ to $35^{\circ}C$ were accepted. No check was made of the method of SST observation, whether bucket or engine intake method etc.

(b) For air temperature, the range accepted was from $15^{\circ}C$ to $39^{\circ}C$.

(c) For surface pressure, the range accepted was from 981 mb to 1030 mb.

(d) Wind speeds from 0 to 99 knots (i.e., from 0 to 50 ms^{-1} approximately) was accepted.

The data exceeding the above range limits were very few. Evidently, Bunker, we presume had used some such criteria while preparing the data set.

The rainfall data for the study has been taken from Mooley and Parthasarathy (1984). Average rainfall over the plains for each monsoon season (June through September) is obtained by weighting each station rainfall by the area of the distribution in which the station is located. Data pertaining to about 306 stations evenly distributed over the plains of India were used.

The data pertaining to Southern Oscillation Index (SOI), has been taken from Shukla and Paolino (1983). Here the SOI refers to the difference in pressure between April and January sea level pressure at Darwin. Darwin is located near one of the nodes of the Southern Oscillation (SO), we have also used the pressure tendency rather than the actual pressure in this study following Shukla and Mooley (1987).

The data on the position and location of the 500 mb ridge along 75^{o}E in April for the period 1948 to 1972 has been extracted from Mooley et al., (1986).

The basic parameters needed for computing the air-sea fluxes were then extracted from the Bunker data set. The latent heat flux (L.H.F), sensible heat flux (S.H.F), wind stress (τ) have been computed following Bunker (1976) using the bulk aerodynamic formulae. The empirical equations used to compute the above fluxes are the following:

$$\tau = \rho_a C_D W^2 \qquad \text{---- (1)}$$

$$\text{L.H.F} = \rho_a L C_E (Q_S - Q_a) W \qquad \text{---- (2)}$$

$$\text{S.H.F} = \rho_a C_P C_H (T_S - T_A) W \qquad \text{---- (3)}$$

Where,

ρ_a = air density.

C_D = C_E $=C_H$ = exchange coefficients.

W = wind speed at 10 m above the sea surface (ms^{-1}).

Q_S = specific humidity at T_S. (gkg^{-1}).

Q_A = specific humidity at T_A. (gkg^{-1}).

L = latent heat of vaporisation.

T_S = sea surface temperature (in ^oC).

T_A = air temperature at 10 m above the sea surface (in ^oC).

C_P = specific heat of air at constant pressure.

A major problem while using the bulk aerdynamic equations for computing the air sea fluxes are the values of various exchange coefficients namely, drag coefficient, C_D, the exchange coefficient for water vapour, C_E and the exchange coefficient for sensible heat, C_H. Sverdrup (1937), Jacobs (1942), Budyko (1963) and numerous others used the above equations and assumed that the coefficients were identical, constant and had a value between 1.4×10^{-3} to 2.3×10^{-3}. Many field, laboratory and theoretical experiments have shown that these coefficients are not identical and that they vary with wind speed and atmospheric stability.

Studies by several authors (Shea (1972); Wu (1968); Deacon and Webb (1962); Wilson (1960) etc.,) both in field and laboratory experiments indicate that the drag coefficients increase with the wind speed. The general variation is from 1×10^{-3} for the low wind speeds to 4×10^{-3} for hurricane winds. Values at very high wind speeds are less certain since there are only few estimates.

Studies of Budyko (1963); Bunker (1952,1972); Holland (1972); Kondo (1973); Riehl and Malkus (1961) have shown that the C_E value increases with speed upto 30 ms^{-1} with a possible decrease above that value. The stability of the air reduces both the C_D and C_E, while the instability enhances the values.

There is evidence from various studies that the heat transfer coefficients may be larger than the water vapour coefficient. Dunckel et al., (1974) established that average C_H value was 1.78×10^{-3} by two methods. Smith and Banke (1975) found that $C_H = 1.5 \times 10^{-3}$, while Muller-Glewe and Hinzpeter (1974) determined that $C_H = 1 \times 10^{-3}$ over the

Baltic Sea. Frieche and Schmitt (1975) have studied the measurements by eight authors, including themselves. They found a strong dependency on stability but did not investigate the dependency on wind speed. They concluded that C_H equals 1.46×10^{-3} for very unstable conditions, 0.97×10^{-3} for moderate winds and instabilities and 0.86×10^{-3} for stable conditions.

In the present study we use the exchange coefficients used by Bunker (1976) and given in tables 1 and 2 for various wind speeds and atmospheric stability conditions. The fluxes have been computed from each individual ship observation and later averaged for different MSQ's for different months.

The fluxes of solar radiation and infrared radiation have been computed (Bunker, 1976) and is as follows:

$$SW = Q_O (1 - \alpha) (1-aN-bN^2) \qquad \text{---- (4)}$$

$$LW = \varepsilon \sigma \theta_a^4 (11.7-0.0023\sqrt{e_a}) (1-cN) + 4 \varepsilon \sigma \theta_a^3 (\theta_s - \theta_a) \qquad \text{---- (5)}$$

where,

SW = incoming solar radiation absorbed by the ocean (Wm^{-2}).

LW = outgoing longwave radiation (Wm^{-2}).

Q_O = shortwave radiation incident on the earths surface on a cloudless day (from a table given in Kondratyev (1969)).

α = albedo of the sea surface (from Payne (1972)).

N = observed mean monthly cloudiness.

a = b = empirical constants = 0.38 (following Bunker (1976)).

ε = emissivity = 0.96

σ = stefan Boltzmann's constant.

θ_a = average absolute temperature of air (in ^oK).

θ_s = average absolute temperature of sea (in ^oK).

e_a = vapour pressure pressure of the air at 10 m above the sea surface (mb).

c = variable cloud cover coefficient.

The net radiation at the sea surface is the incoming solar radiation absorbed by the ocean less the outgoing radiation and is given by :

$$R = SW - LW \qquad \text{---- (6)}$$

The net heat gain by the ocean (H.G.O) is given by the net radiation absorbed minus the sensible and latent heat fluxes at the surface, and is given by:

$$H.G.O = R - (L.H.F + S.H.F) \quad ---- (7)$$

The meridional heat transport can be estimated in three different ways, (a) Residual method (b) Direct estimates and (c) The surface energy balance method.

The residual method calculates the oceanic flux (F_o) as the difference between the net radiation (R_{net}) received at the top of the atmosphere and the divergence of the atmospheric flux (F_a), and is given by:

$$F_o = R_{net} - \text{div } F_a \quad ---- (8)$$

The direct estimates are made by vertically integrating the fields of the products of meridional velocity and temperature. The surface energy balance method uses the balance at the ocean-atmosphere interface. The balance at the surface of the ocean can be written as

$$H.G.O = S_o + \text{div } F_o = SW - LW - (L.H.F + S.H.F)$$

where,

H.G.O = heat gain at the ocean surface (Wm^{-2}).

div F_o = oceanic flux divergence (Wm^{-2}).

S_o = heat storage (Wm^{-2}).

SW = incoming shortwave solar radiation absorbed by the ocean (Wm^{-2}).

LW = outgoing longwave radiation (Wm^{-2}).

L.H.F = latent heat flux (Wm^{-2}).

S.H.F = sensible heat flux (Wm^{-2}).

Again in the long term mean, the term S_o vanishes as it can be safely assumed that there are no long term temperature changes. The above equation then reduces to:

$$H.G.O = \text{div } F_o$$

The above equation indicates that the heat gain at the oceanic surface can be used as an estimate of oceanic flux divergence. The meridional heat transport then can be calculated by using the Green's theorem by integrating the energy flux divergence with respect to area using appropriate boundary coniditons. The most common assumption (and probably the best) is that the flux vanishes at the northern or southern boundary of the ocean basin. The transport for the Indian Ocean has been computed assuming zero net flux at 30^oN. Transport values were then computed for each ten degree latitude belts.

The zonal anomaly of the sea surface temperature were computed as follows: The SST values for every two degree latitude-longitude grid points were estimated by visual interpolation (for both global operational SST computation (GOSSTCOMP) as well as climatological charts).

The zonal anomalies (T_z) were then calculated as follows:

$$T_z = T - \overline{T},$$

where T and $\overline{T}$ are the observed grid point and zonal mean SST's respectively.

ERRORS

The errors involved in the study can be broadly categorized as systematic and random errors. The main source of systematic errors are : a) uncertainity of bulk aerodynamic formulae in the computation of accurate fluxes b) bias from inadequate data sampling in both time and space and c) instrumental , observational and reporting errors.

Blanc (1987) has shown that the average accuracies of the bulk method ranges from 35% to 105% for stress magnitudes of 0.025 - 1.0 Nm^{-2}, 35%-220% for sensible heat flux magnitudes of 5-150 Wm^{-2} and 40%-215% for latent heat flux magnitudes of 10-300 Wm^{-2}.

It should be noted here that these large inaccuracies arise because of the utilization of extreme valuues in different ranges as can be seen from Table 1. For example, the value of C_D for 5 ms^{-1} is given as 0.06 X 10^{-3} whereas it has a value of 0.77 X 10^{-3} (a factor of 13) for a value of 5.01 ms^{-1}, for the same air-sea temperature difference. We realise this and presume that the data set pertains to the zones of values where the coefficients change gradually.

Weare and Strub (1981) have shown that the errors can occur due to inadequate sampling in both space and time. This can be mainly due to the uneven sampling within the specified time and also uneven data distribution within the grid. For example, in the case of grid along which a major shipping lane exists there will be large errors in the fluxes computed because the data density of other regions will be meagre and hence a true representation of the fluxes for the grid will not be possible. The same holds good for regions where the tropical cyclones and monsoon depressions exist.

Recent study of Vinayachandran et al., (1989) have shown that there exists bias from observation techniques and instrumentation. By comparing the data obtained from the research vessel ORV Sagar Kanya and the published marine weather reports from Indian Daily Weather Report (IDWR), they have found that the latent heat flux was less by about 35% in the case of IDWR. In addition, the inaccurate positioning of the anemometer and various meteorological equipments also result in large errors.

The main source for random errors is the non uniform techniques and reporting and archiving methods (Hsiung, 1984). This is most evident in the case of the radiative and latent heat fluxes. An inaccurate observation of cloud cover can result in large errors in the radiative flux term, since this parameter unlike the other observations is largely observer dependent. In the case of latent heat flux, since the flux is a function of both the transfer coefficient and wind speed, and the transfer coefficient again being a function of wind speed, an error in the wind speed can result in large error in latent heat flux.

These types of errors in general decrease with increasing number of observations and by the methods of averaging both in space and time. In the present study, the errors are likely to be at their minimum since we have analysed for ten degree square grids (MSQ's) and there are sufficient number of observations for the study period and the data is more or less uniformily distributed (Figure 2a and 2b) and we are examining only the longterm annual and seasonal means. The errors are also expected to be uniformily distributed and do not alter the conclusions.

TABLE 1

Drag coefficients C_D X 10^3

(Reproduced from Bunker (1976)).

Wind speed (ms^{-1})	4.9 to >5.0	0.9 to 1.0	0.1 to 0.2	-0.3 to -0.2	1.1 to -1.0	-4.9	<-5.0
	Air minus sea surface temperature class (K)						
0.01-5.0	0.06	0.60	0.98	1.20	1.32	1.56	1.80
5.01-10.0	0.77	1.30	1.43	1.54	1.60	1.78	1.86
10.01-15.0	1.47	1.72	1.80	1.87	1.90	2.00	2.10
15.01-20.0	1.95	2.04	2.10	2.16	2.22	2.25	2.32
20.01-25.0	2.26	2.30	2.35	2.40	2.42	2.44	2.48
25.01-30.0	2.52	2.54	2.57	2.60	2.62	2.63	2.64
30.01-35.0	2.78	2.79	2.80	2.80	2.80	2.80	2.80
35.01-40.0	3.00	3.00	3.00	3.00	3.00	3.00	3.00
40.01-50.0	3.20	3.20	3.20	3.20	3.20	3.20	3.20
>50.0	3.40	3.40	3.40	3.40	3.40	3.40	3.40

TABLE 2

Exchange coefficients $C_E \times 10^3$

(Reproduced from Bunker (1976)).

Wind speed (ms^{-1})	Air minus sea surface temperature class (K) >5.0	4.9 to 1.0	0.9 to 0.2	0.1 to -0.2	-0.3 to -1.0	1.1 to -4.9	<-5.0
0.01-3.0	0.07	0.30	0.72	1.32	1.65	2.05	2.52
3.01-6.0	0.22	0.67	1.12	1.34	1.45	1.68	2.01
6.01-9.0	0.69	1.17	1.36	1.44	1.46	1.58	1.79
9.01-12.0	1.06	1.36	1.48	1.53	1.58	1.65	1.79
12.01-15.0	1.39	1.58	1.61	1.64	1.68	1.74	1.84
15.01-20.0	1.59	1.68	1.75	1.80	1.82	1.86	1.94
20.01-25.0	1.74	1.79	1.83	1.86	1.86	1.86	1.93
25.01-30.0	1.81	1.84	1.85	1.86	1.87	1.88	1.90
>30.0	1.86	1.86	1.86	1.86	1.86	1.86	1.86

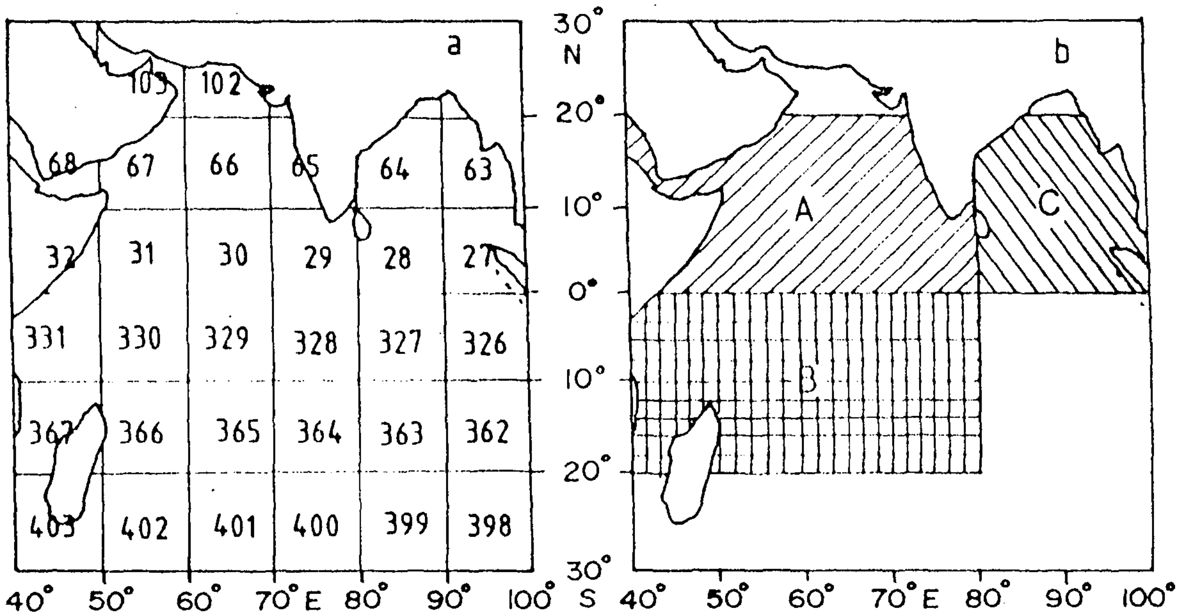
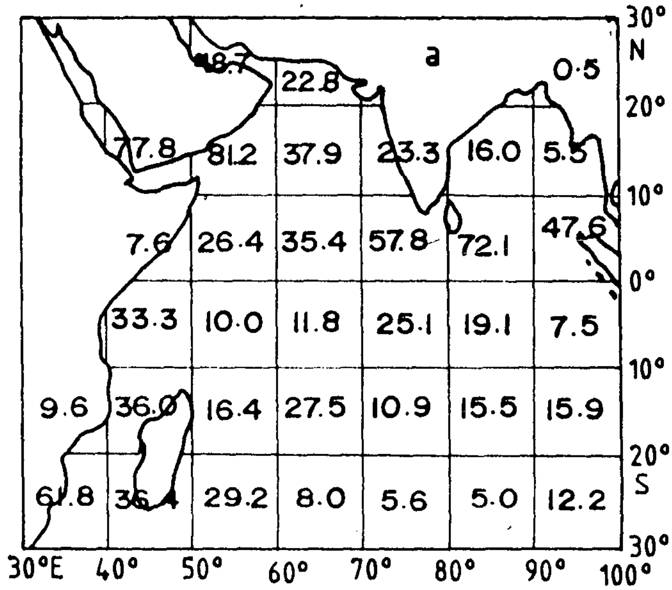


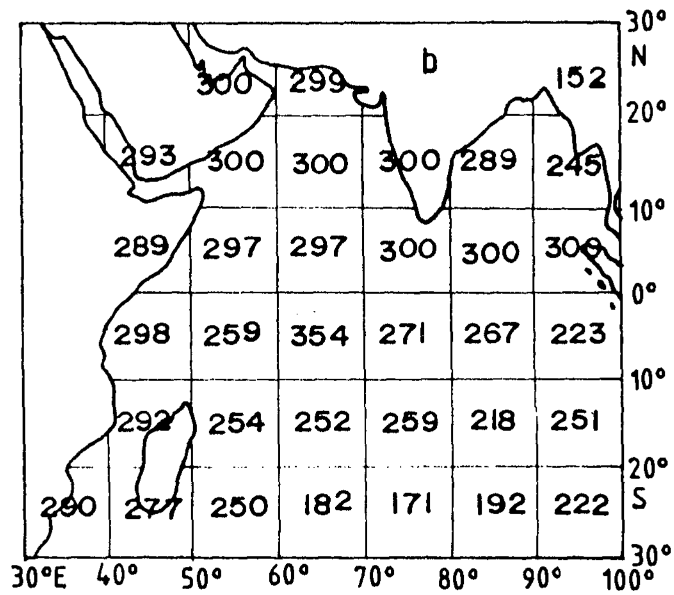
Fig. 1

a Marsden square numbers used in the present study.

b Study areas used to compute mean evaporation over Arabian sea (A) , Southern hemisphere (B). and Bay of Bengal (C)



Total number of observations ($\times 10^3$) used in the present study.



Number of months out of a possible 300 months.

Fig. 2

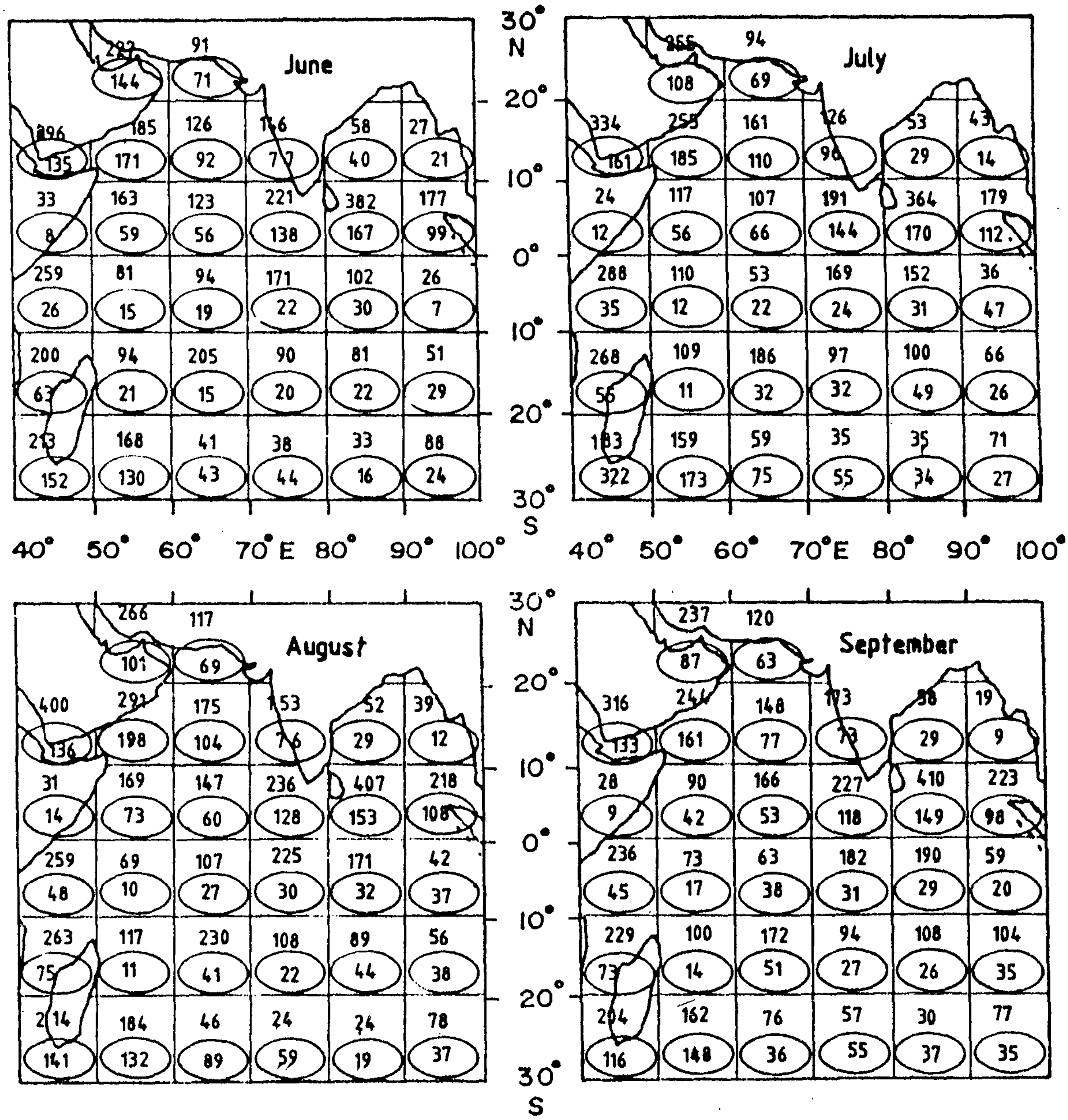


Fig. 3

Mean monthwise distribution of data density for bad (open) and good monsoon (circled) composites.

CHAPTER III

MEAN ANNUAL AND SEASONAL FLUXES OVER THE TROPICAL INDIAN OCEAN

In recent years, there has been an increased interest in the study of air-sea fluxes of the tropical oceans (Bunker, 1976,1980; Bunker and Worthington, 1976; Hastenrath and Lamb, 1978; Hastenrath and Lamb, 1979a & 1979b; Weare , Strub and Samuel, 1981; Hsiung, 1986; Ramesh Kumar and Gangdhara Rao, 1989). The need for obtaining accurate air-sea fluxes need not be over emphasised, especially over region like Indian Ocean which differs drastically from the other oceans, because it undergoes dramatic variations in its atmospheric and surface circulation by a semiannual phenomenon known as monsoons.

In the present chapter we examine the spatial patterns of the annual and seasonal mean fields of air and sea surface temperatures (T_a & T_s), wind stress (τ), net radiation (R), heat gain over the ocean (H.G.O) and the total heat loss (Q). In addition, the mean annual meridional energy transport and the moisture flux for the study area is presented.

Seasonal Variation of air-sea temperatures and fluxes:

To see the seasonal patterns of the components of the surface energy budget, longterm monthly means of SST, air temperature, wind stress, E.R.S, total heat loss and H.G.O are calculated and the results for one month of each season (January (JAN), April (APR), July (JUL) and October (OCT) to represent the various seasons, namely, the winter, premonsoon, monsoon and post monsoon respectively) are presented.

a) Sea surface temperature:

Our present values of SST compare well with the previuos studies of Hastenrath and Lamb (1979 a & b) and Hsuing (1984). An interesting feature of the above figure is that the SST is always greater than 28^{o}C over the Bay of Bengal area.

b) Air temperature:

Figure 5 depicts the seasonal variation of air temperature over the tropical Indian Ocean.The air temperature pattern more or less follows the sea surface temperature pattern over most of the study areas. The distribution is more or less latitudinal especially over the southern Indian Ocean.

c) Wind stress:

The seasonal variation of wind stress shows a pronounced maximum during the southwest monsoon season due to the effect of strong low level winds over the Somalia area (in the month of July) as compared to the other seasons (Figure 6). It is almost three times the values observed in the month of January, especially off the coasts of Arabia and Somalia. The minimum values are observed in the month of April, over the entire study area.

d) Effective radiation at sea surface:

The maximum values of the effective radiation are observed in the month of April as compared to the other months (Figure 7). The minimum values over the tropical Indian ocean are observed in the winter season (January). In general the ERS values over the eastern Indian Ocean area are less as compared to the western Indian Ocean region.

e) Total heat loss (L.H.F + S.H.F):

The tropical Indian Ocean area is one of the major regions where the ocean loses heat to the atmosphere in the form of latent and sensible heat. Figure 8 shows the seasonal variation of total heat loss over the study area. The maximum heat loss occurs during the southwest monsoon season (of the order of 200 Wm^{-2}) over the central Arabian Sea area, equally high losses are observed over the southern and central Indian Ocean (MSQ 401). The minimum losses are observed in the pre-monsoon months (of the order of 75 Wm^{-2}) off the coasts of Arabia.

f) Heat gain over the ocean surface:

In the month of January (figure 9), the Arabian Sea loses heat to the atmosphere and starts gaining heat during the premonsoon season. The maximum heat gain over the north Indian Ocean area is observed in the month of April. The heat gain over this area decreases with the onset of monsoon.

Annual mean statistics of the surface fluxes

In order to characterize the long term behaviour of SST, the long term annual mean and variance were computed and presented in figure 10. Figure 10a presents the 25 year mean annual SST for the tropical Indian Ocean. The distribution of the annual SST pattern is latitudinal except over the regions where upwelling (off Arabian and Somalia coasts) and western boundary currents (Bay of Bengal) dominate. In the Indian Ocean north of equator and east of 60°E, there is large body of water with temperature greater than 28°C. This can be one of the major reasons for this region being ideal for the formation of monsoon depressions and tropical cyclones. The mean annual distribution of SST agrees well with the previous study of Hsiung (1984). Figure 10b presents the annual SST variances for the study area. The largest variances (> 0.60 dynes cm^{-2}) prevail over the Bay of Bengal, south-east African and Arabian coasts.

Figure 11 shows the mean annual T_a, and variance for the study period. The spatial pattern of air temperature (Figure 11a) more or less follows the SST pattern except that the 28°C isotherm covers only a small region. In this case also the largest variances are observed in the Bay of Bengal and south east African coast (Figure 11b).

The mean annual wind stress pattern is depicted in figure 12a. The largest stress values (> 1.0 dyne cm^{-2}) are observed off Somalia and Arabian coasts. An equally high value is observed in the southern Indian Ocean between 10°S - 20°S. The lowest values are observed just south of equator. These stress values agree well with the mean annual wind speed pattern depicted for the Indian Ocean by Hsiung (1984). The maximum variances of the stress values are observed off the Arabian and Somalia coasts which are upwelling regions and the Bay of Bengal and the south east African coast (Figure 12b).

The long term mean annual net radiation is shown in figure 13a. Even though the spatial distribution agrees well with the previous studies of Hastenrath and Lamb (1979b) and Hsiung (1984), our values are higher by about 60 to 80 Wm^{-2}. These differences may be due to the different formulas used or the different study periods. Maximum mean annual net radiation values are observed off the Arabian and Somalia coasts and the minimum values are found in the eastern portions of the tropical Indian ocean. Maximum annual variances are observed over the Bay of Bengal (Figure 13b).

Figure 14a presents the mean annual total heat loss (sum of latent and sensible heat flux) over the tropical Indian ocean. The present estimates are higher than those estimated by Hastenrath (1982) and Hsiung (1984). These differences can be largely due to the different exchange coefficients used and partly due to the different study periods. From the figure it can be seen that the maximum heat loss occurs over the central Arabian sea and the southeastern region of the study area. The maximum variances (Figure 14b) are observed in the Bay of Bengal (MSQ 64), south central Arabian sea (MSQ 30) , off Somalia coast (MSQ 67) and the south east African coast (MSQ's 367 and 404).

On an annual basis, almost the entire northern Indian Ocean area gains heat (Figure 15a). In the southern tropical Indian Ocean area, the H.G.O is positive in the western region and negative in the eastern region. These values are in good agreement with those of Hastenrath and Lamb (1979b) and Hsiung (1984). An analysis of the variance (Figure 15b) shows that the maximum variablity occurs over the east coast of India, off the coasts of Arabia and Somalia, over the south central Arabian sea and the south east African coast.

Moisture Flux:

From the equation of conservation of Water in the atmosphere (Rasmusson, 1972), we have,

$$\frac{\partial W}{\partial t} + \nabla \cdot Q_W = E - P$$

where W is the total column water mass, $\nabla . Q_W$ the divergence of the moisture flux throughout the column, E the rate of evaporation and P the rate of precipitation. $\frac{\partial W}{\partial t} = 0$ for the annual mean.

Since the bulk of the moisture exists in the lower part of the atmosphere, we can interpret figure 16 in terms of the column divergence/convergence.

The annual mean precipitation values used in the present study are the INSAT - 1B derived precipiation values for the year 1987 over the tropical Indian Ocean using the infrared channel of the Very High Resolution Radiometer (VHRR) sensor working in the range 10.5-12.5 um. We assume that there are no large interannual variations in the oceanic precipitation for the study area. The reason for using the satellite derived precipitation is the non availability of oceanic precipitation values for the tropical Indian Ocean. Rao et al (1981) ; Vinayachandran and Ramesh Kumar (1989) have validated the satellite derived precipitation values with the observed island station data, and have found that they differ by about 50% and 25% respectively with the observed precipitation data over the island stations.

Figure 16 presents the moisture flux divergence/ convergence at the sea surface over the tropical Indian Ocean. The most interesting feature of the above figure is the region of large scale convergence (dashed area) in the eastern Indian Ocean, especially Bay of Bengal area. This indicates that this region is highly conducive for large scale convective activity like the formation of monsoon depressions and tropical cyclones round the year. From this it can be seen that the evaporation exceeds precipitation over all the tropical Indian Ocean except the eastern half of it. Thus it further emphasises the role of the Arabian Sea and the cross-equatorial moisture flux than the moisture from the Bay of Bengal region for the summer monsoon rainfall over the Indian subcontinent.

Table 3 gives a comparison of the water vapour flux values for the AS (Vinayachandran and Ramesh Kumar, 1989) during several contrasting monsoon seasons. An analysis of table 3 shows that the moisture flux over the AS exihibits large intraseasonal and interannual variations. The values for 1975 and 1979 were obtained using the upper air data, whereas for the rest of the years it is obtained as the difference between the E - P estimates. Hence the large variability in the moisture flux divergence values can be attributed to the precipitation fluctations or the errors in the precipitation estimation.

A comparison of our meridional heat transport estimate with those of previous studies is shown in Table 4. The direction of transport is southward at all latitude belts with the exception of higher latitudes in the southern hemisphere. Our estimates of a southward transport in the Indian Ocean are in agreement with that of Hsiung (1983) and Hastenrath (1982) but differ in magnitude. These differences can be due to three reasons: (i) different criteria used for boundary partitioning (of the Indian Ocean area) in the above studies. In this study we have conifined the eastern boundary of Indian Ocean at 100^{O}E, while Hastenrath (1982) has extended upto 120^{O}E and Hsiung (1984) upto 120^{O}E (as the limit) for the northern hemisphere and 150^{O}E for the southern hemisphere (ii) large interannual variations in the energy balance over the study area and (iii) different study periods used by the above authors.

TABLE 3

Moisture flux divergence values over the Arabian Sea for different years. Units: 10^{10} tons/day.

Month/Year	1964	1973	1974	1975	1979	1987
June	0.51	0.36	1.90	3.10	0.02	-0.02
July	0.48	1.38	2.40	3.00	0.05	2.55
August	-0.27	----	2.31	3.50	0.46	0.70
September	0.82	----	----	2.80	-0.23	0.44

TABLE 4

Comparison of various estimates for annual meridional heat transport for the tropical Indian Ocean (in 10^{14} W).

Latitude	Present study	Hsiung (1984)	Hastenrath (1982)
30°N	----	----	----
20°N	-0.55	-0.51	
10°N	-4.95	-3.65	
Equator	-6.52	-8.30	-4.80
10°S	-9.74	-13.68	
15°S		-15.79	-7.70
20°S	-10.04	-14.93	
30°S	-9.04	-13.25	-4.90

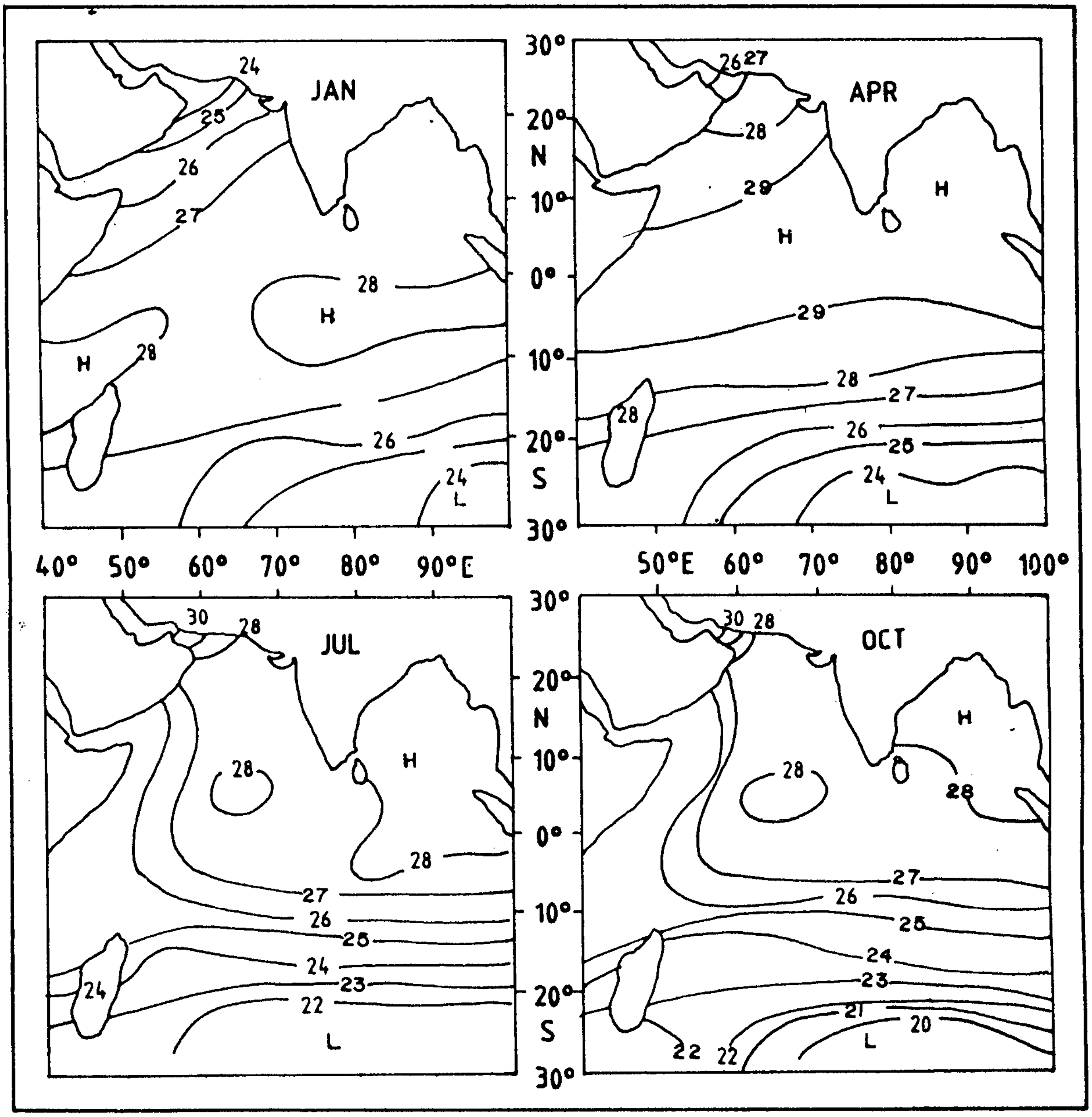


FIG. 4 SEA SURFACE TEMPERATURE - SEASONAL VARIATION (°C)

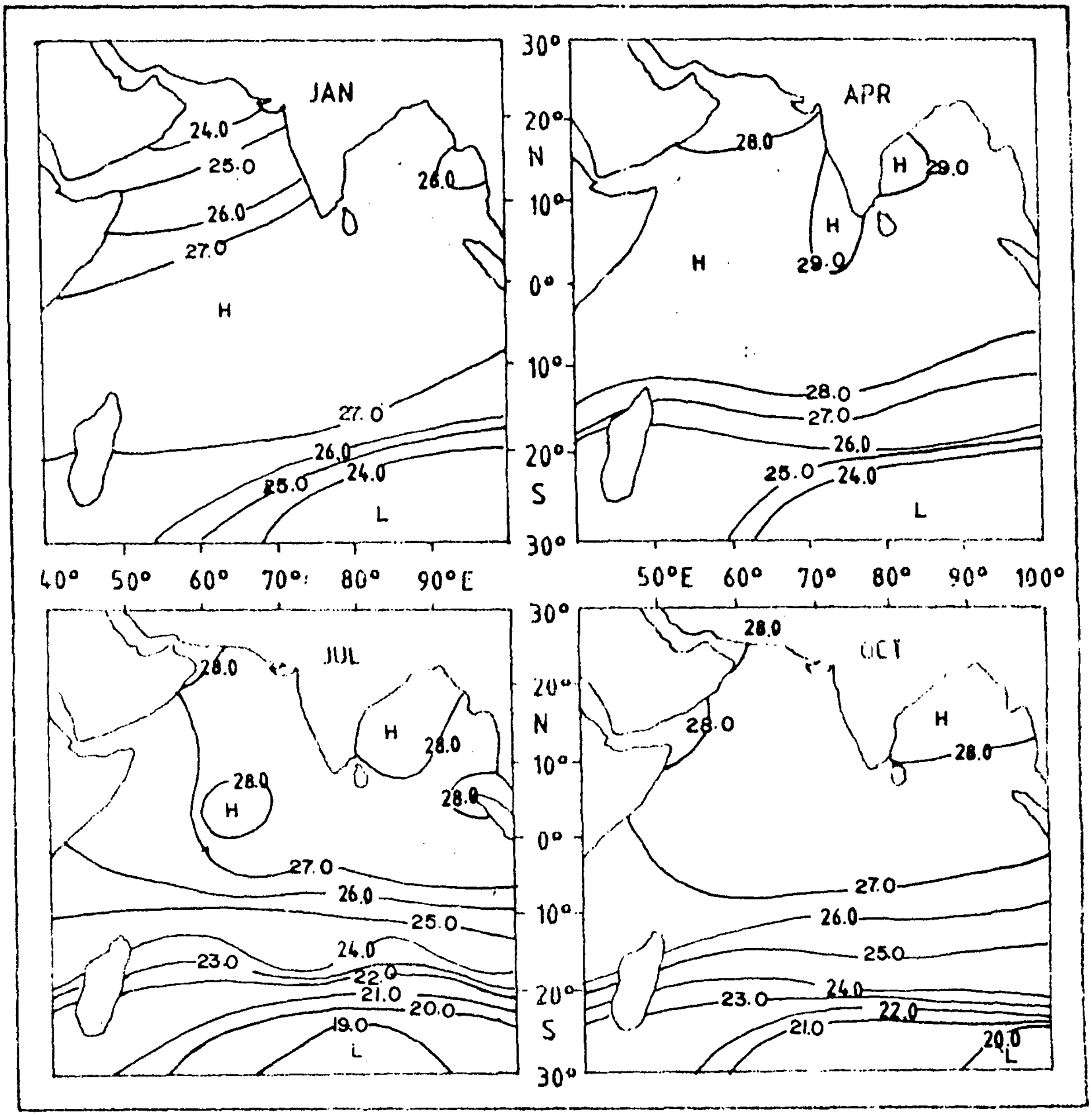


FIG. 5 AIR TEMPERATURE-SEASONAL VARIATION (°C)

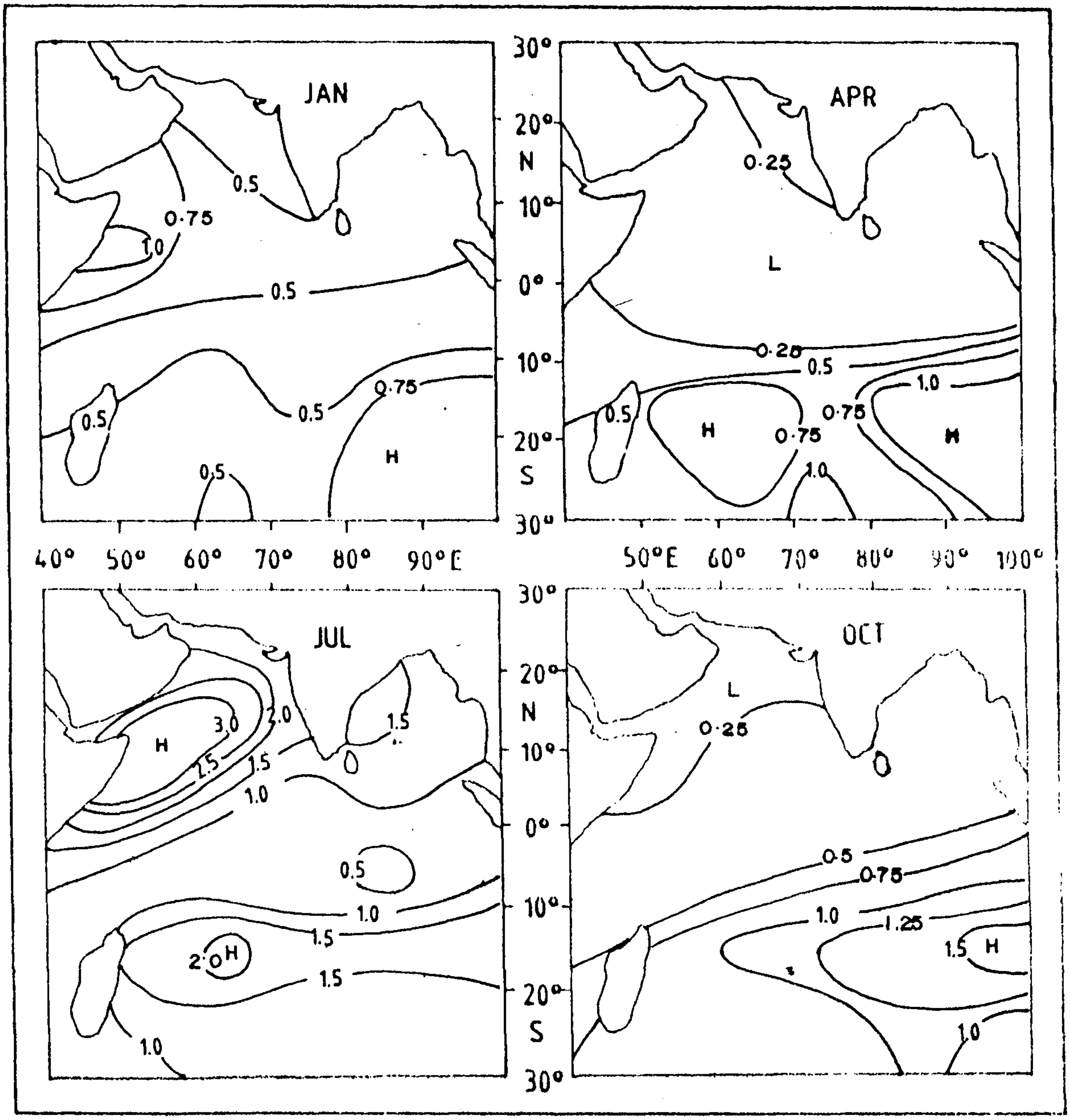


FIG. 6 WIND STRESS - SEASONAL VARIATION (Dynes cm^{-2})

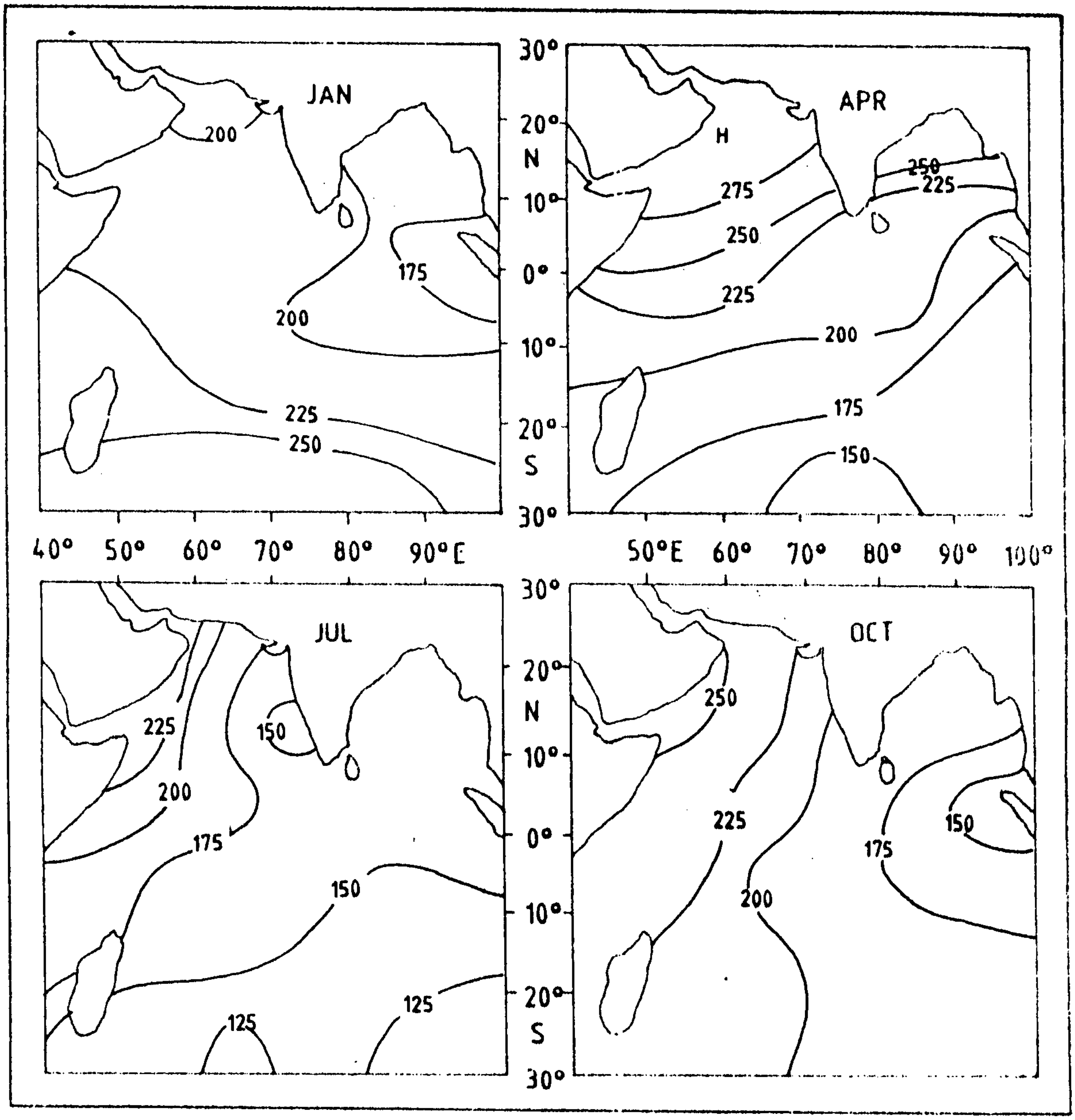


FIG. 7 EFFECTIVE RADIATION AT SEA SURFACE-SEASONAL VARIATION (Wm^{-2})

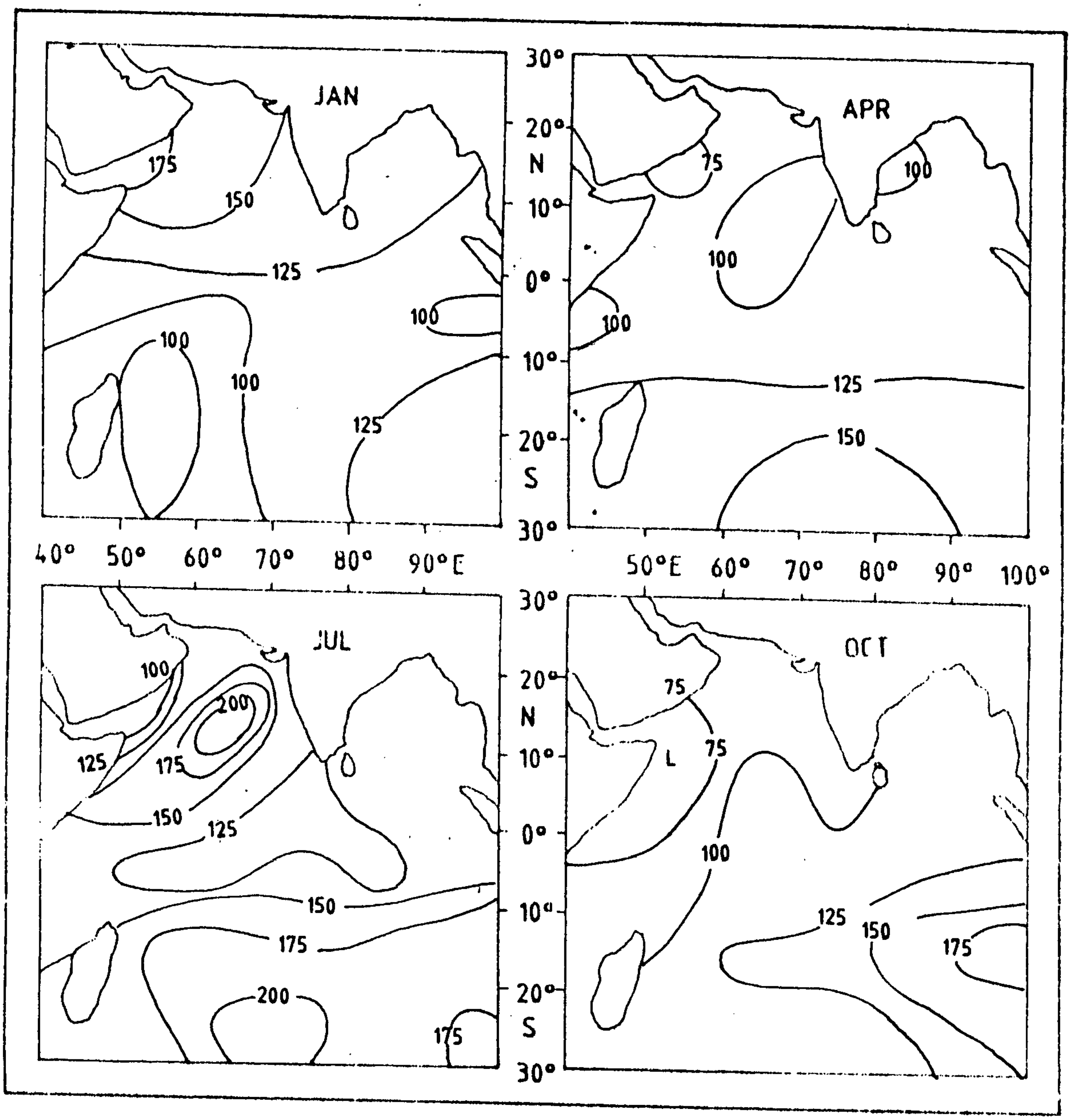


FIG. 8 TOTAL HEAT LOSS - SEASONAL VARIATION ($W m^{-2}$)

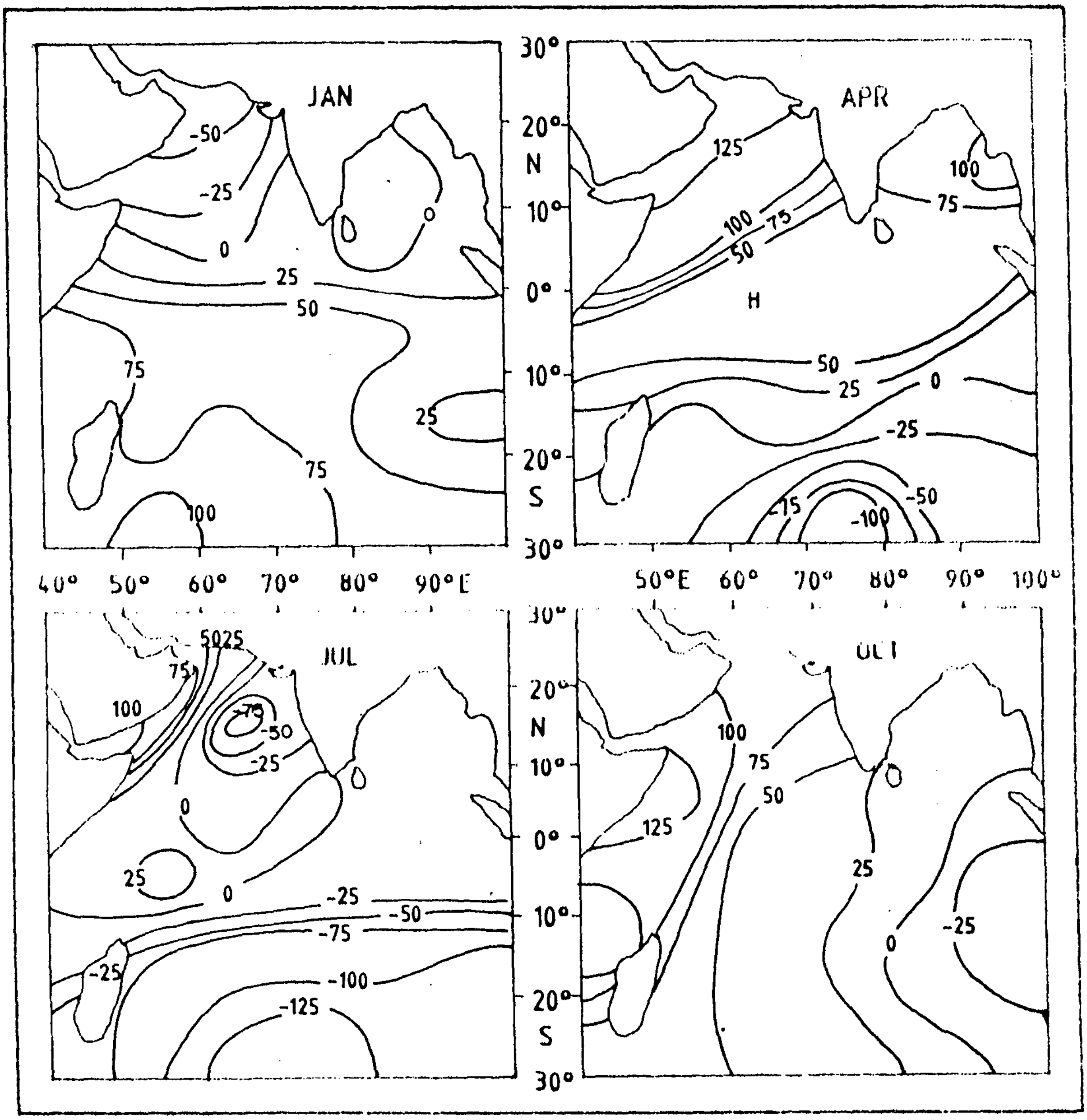
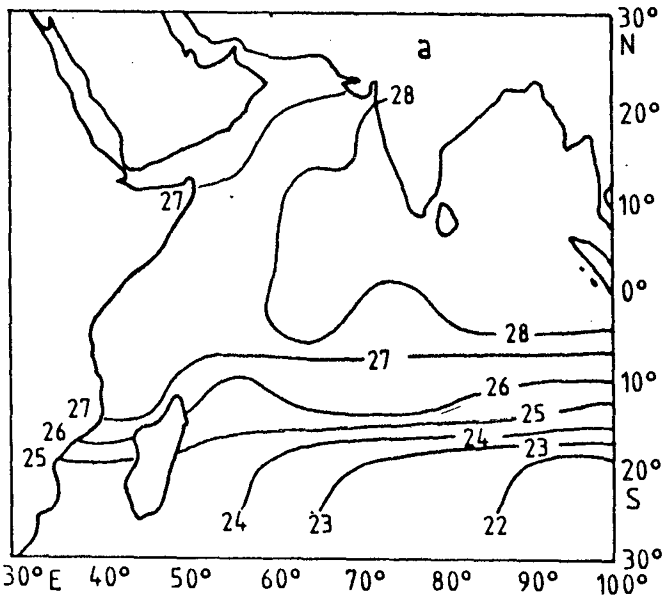
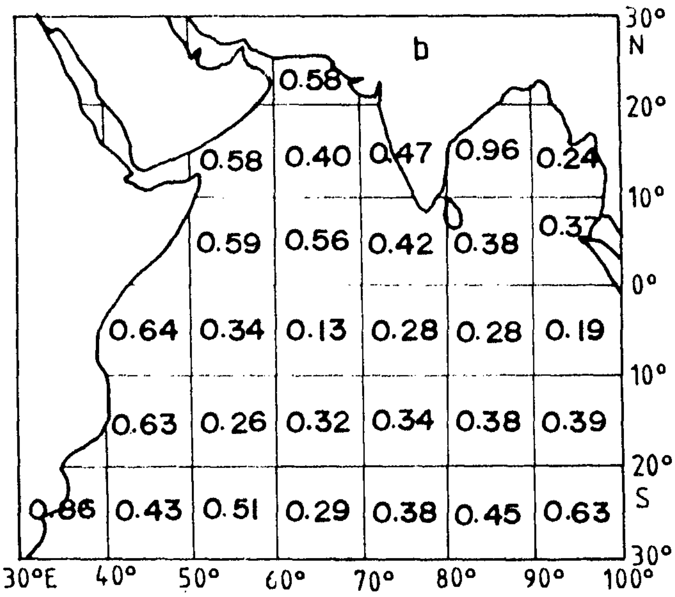


FIG. 9 HEAT GAIN OVER THE OCEAN SURFACE - SEASONAL VARIATION (Wm^{-2})

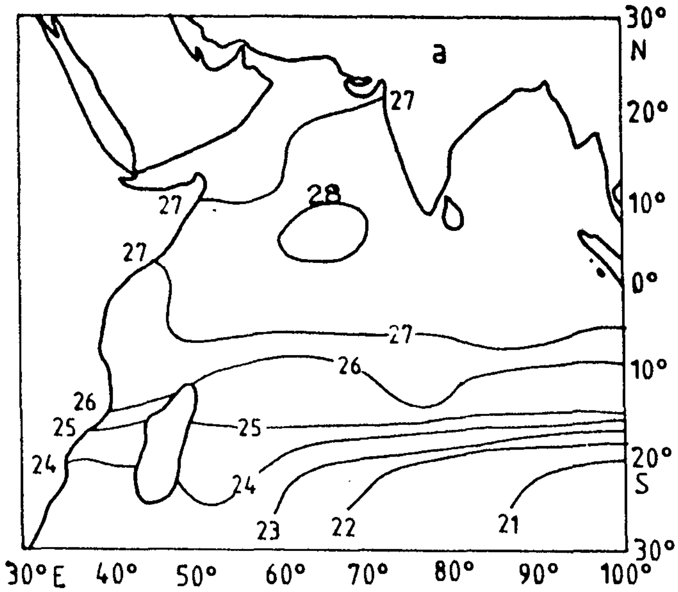


Annual mean sea surface temperature (°C)

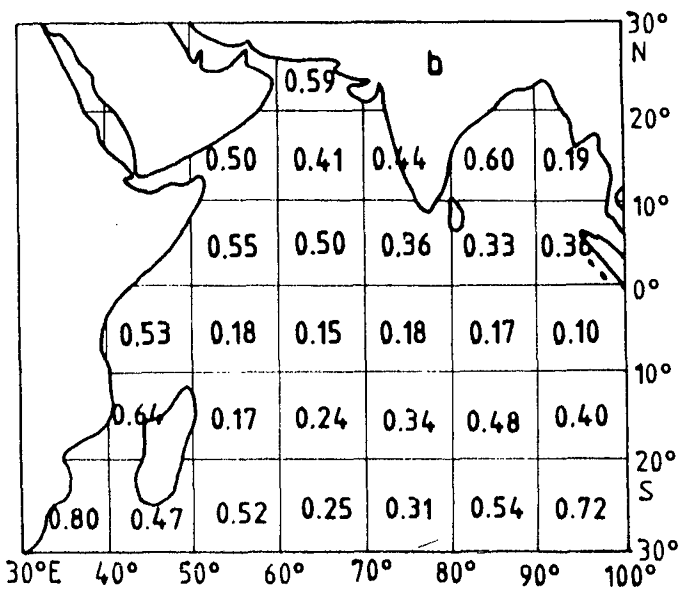


Annual SST variance (°C)

Fig. 10

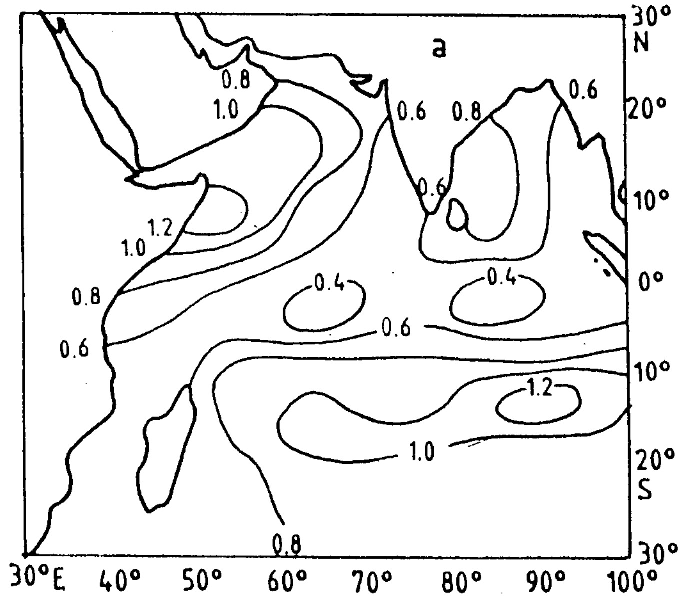


Annual mean air temperature (°C)

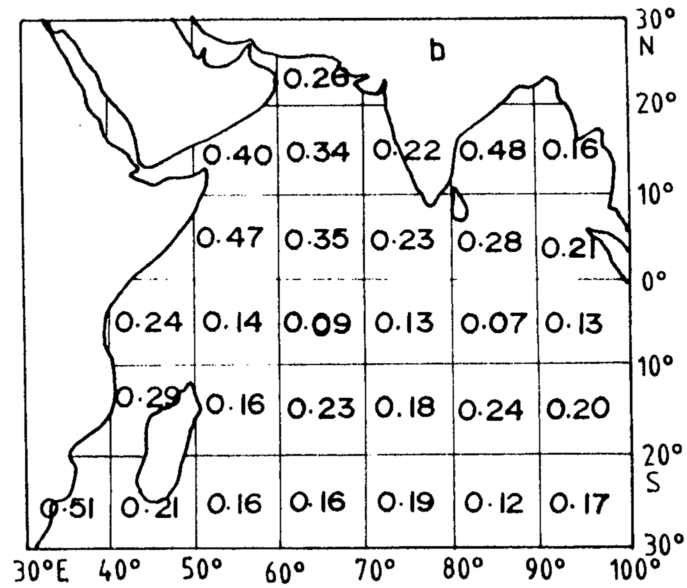


Annual air temperature variance (°C)

Fig. 11

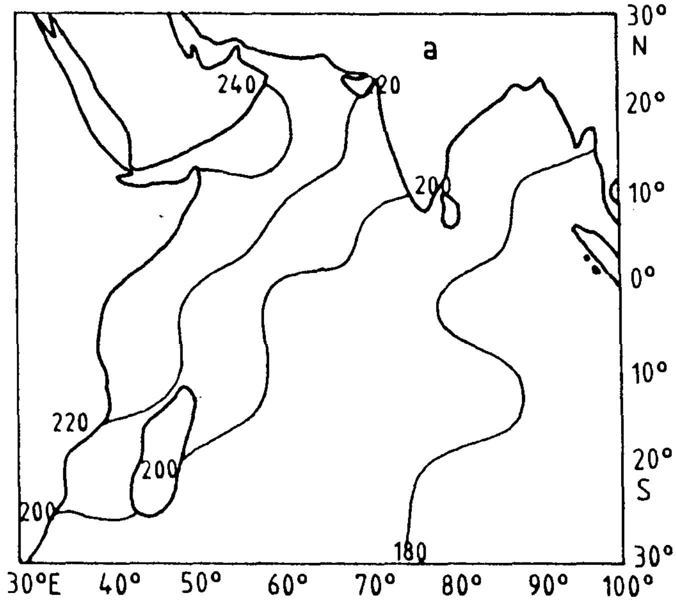


Mean annual wind stress (dyne cm^{-2})

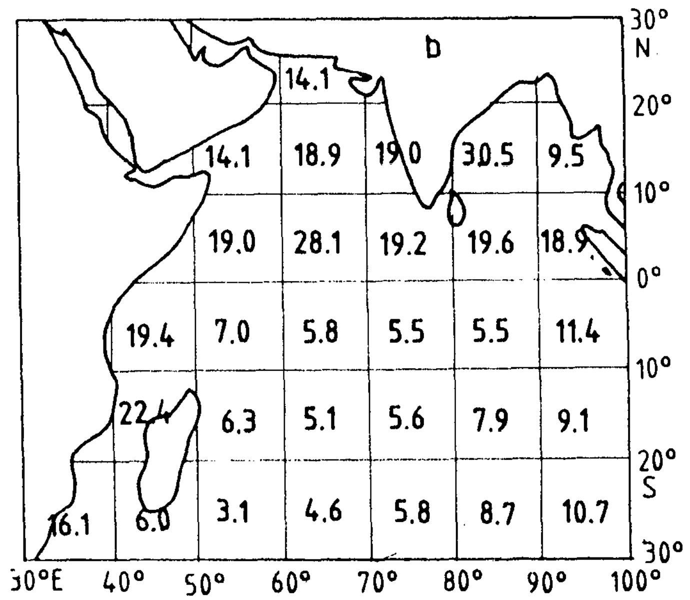


Annual wind stress variance (dyne cm^{-2})

Fig. 12

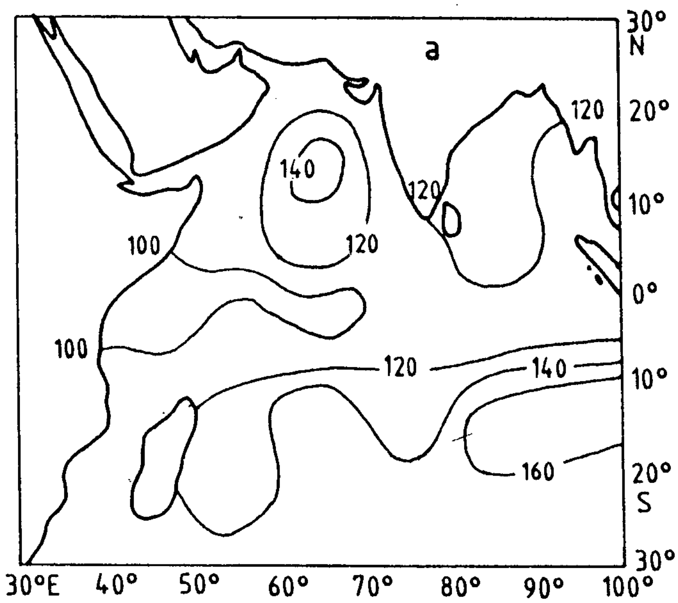


Mean annual net radiation (Wm^{-2})

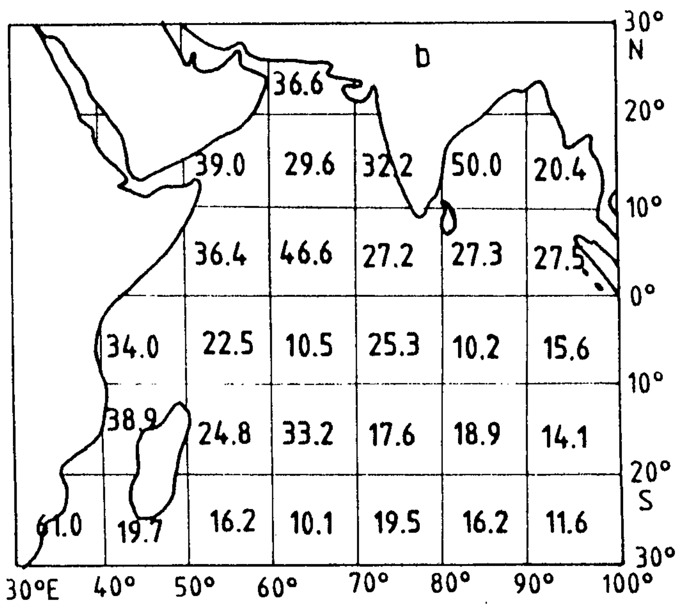


Annual net radiation variance(Wm^{-2})

Fig. 13

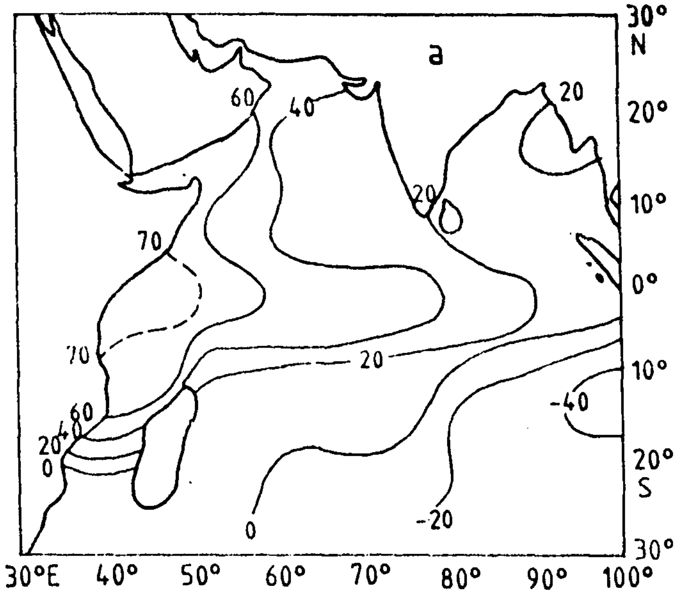


Mean annual total heat Loss(Wm^{-2})

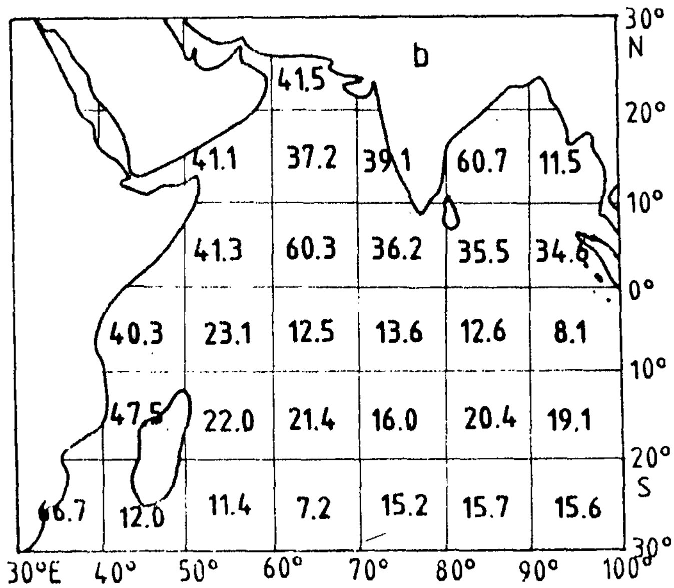


Annual total heat Loss variance(Wm^{-2})

Fig. 14

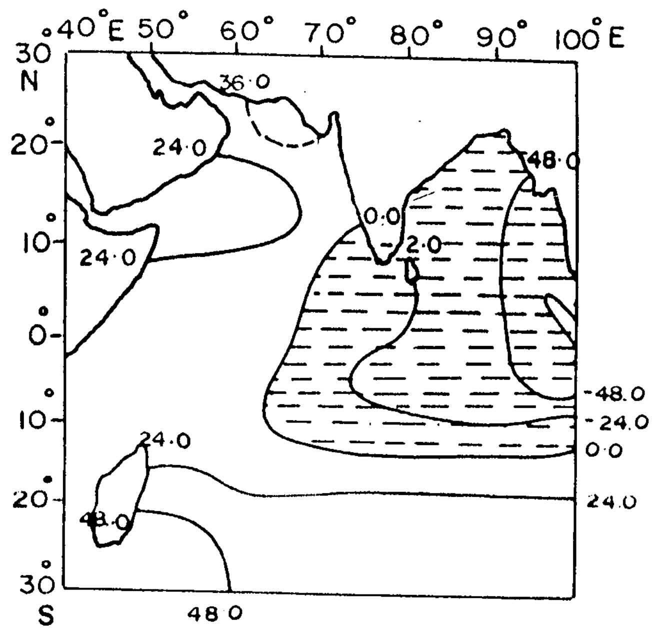


Mean annual heat gain (Wm^{-2})



Annual heat gain variance (Wm^{-2})

Fig. 15



Mean annual E-P chart (cm / year)

Fig. 16

CHAPTER IV

AIR SEA INTERACTION OVER THE TROPICAL INDIAN OCEAN DURING SEVERAL CONTRASTING MONSOON YEARS

The summer monsoon (June to September) period plays a vital role in the economy of the Indian subcontinent as most of the annual rainfall in the various meteorological subdivisions is received during this period. The role of sea surface temperature (SST) and source of moisture for monsoon rainfall has been a controversial subject for years (Pisharoty, 1965; Saha and Bavadekar, 1973; Saha, 1974; Shukla, 1975, 1987; Ramamurthy et al., 1976; Shukla and Misra, 1977; Ghosh et al, 1978; Washington et al, 1977; Weare, 1979; Rao et al, 1981; Druyan et al, 1983; Howland and Sikdar, 1983; Cadet and Diehl, 1984; Pearce and Mohanty, 1984; Joseph 1981; Joseph and Pillai,1986; Ramesh Kumar et al, 1986a & b; Cadet and Greco,1987; Sadhuram and Ramesh Kumar, 1988; Rao and Goswami, 1988; Ramesh Kumar and Sadhuram, 1988).

On the role of SST for predicting summer monsoon rainfall over India:

Ramesh Kumar et al (1986a) have analysed the satellite derived sea surface temperature data over the tropical Indian Ocean for the years, 1979 (bad monsoon) and 1983 (good monsoon) from a predictive point of view. Figure 17 gives the departure from normal of monsoon rainfall of various meteorological subdivisions of India for the years 1979 and 1983. Some of the salient features of this study are the following:

Monthly variation of SST:

The weekly averaged SST obtained from the Global Operational Sea surface temperature Computation (GOSSTCOMP) charts have been further averaged to give the monthly mean SST. Figure 18 gives the monthly variation of mean SST for three representative stations A, B and C in the sea off the Somali coast (10°N and 52°E), south central Arabian Sea (10°N and 60°E) and south central Bay of Bengal (10°N and 90°E) respectively, from May to September for the years 1979 and 1983 along with the climatological mean.

At station A, the climatological values of SST (Hastenrath and Lamb, 1979a) drop sharply from May onwards, whereas in 1979 and 1983, the SST decrease from May to June is comparatively less. One would normally expect the climatological values to lie between the good and bad monsoon values, but here climatological values are lower than both the years which can be mainly due to the different sources of data namely ship and satellite data. However, the May to June cooling is more (less) pronounced in 1983 (1979), the year of excess (deficit) rainfall. The rate of cooling can be taken as indicative of the intensity of upwelling in this area. The climatological values as well as the 1979 values show increasing temperatures from August to September, while in 1983, the temperature continues to decrease during this period. This may be due to the late withdrawal of southwest monsoon in 1983 and the persistence of stronger winds off Somali coast and consequent upwelling for a longer period. However, the climatological temperature values in this area are lower than those recorded in 1979 and 1983.

At station B there is little difference in the monthly mean SST variation between 1979 and 1983 and the values for both the years compare well with the climatological data, though here also the climatological values are generally lower. However, the differences are not as high as station A.

At station C, in 1983 the monthly mean SST were greater than normal from May to July, and less than normal from August to September. The values were nearly normal in 1979.

Reappearence of 27^{o}C isotherm:

An analysis of the behaviour of the 27^{o}C isotherm in the Arabian sea, for the years 1979, 1981,1982 and 1983 showed that this isotherm was absent throughout the premonsoon month of May off the Somalia coast and appeared with the onset of southwest monsoon over Kerala coast (Table - 5). Geostationary satellite wind data (Young et al, 1980) for 1979 showed that the appearance of the 27^{o}C isotherm off the Somalia area coincided with the establishment of the low level jet over the central Arabian Sea.

Longitudinal variation of SST in July:

Figure 19 gives the longitudinal variation of SST's in July for the years 1979 and 1983 along with the climatological mean values for the latitudes 20°N, 10°N and Equator. The figure clearly shows that there is larger temperature difference between the western and eastern portions of the Indian ocean during a good monsoon (1983) than during a poor monsoon season (1979). This east-west temperature gradient is more at 20°N and 10°N as compared to that at the equator. At 20°N the maximum SST is observed around 66-70°E and the minimum is observed at 58°E near the Arabian coast. The maximum range of SST is 3°C (2°C) in 1983 (1979). At 10°N the maximum SST's are observed from 68 to 72°E and the minimum around 52°E near the Somalia coast. The maximum range of SST is 3°C (2°C) in 1983 (1979). At the equator, in the region west of 60°E, there is strong (weak) temperature gradient during the good (bad) monsoon year. The temperature gradient in the western part of the equator during 1983 may be due to the strong surface winds (ORV Sagar Kanya 1 *st . Cruise data) and strong cross equatorial flow. The weak temperature gradient during 1979 was due to weak surface winds and weak cross equatorial flow (Geostationary satellite data).

Saha (1970) has shown that at the equator, pressure and SST are negatively correlated. We assume that this relationship holds good for the Arabian Sea also. Thus the large east-west temperature gradient observed during 1983 was favourable for strong low level westerly winds and intense evporation over Arabian Sea.

Zonal anomaly of SST:

Charts of weekly zonal anomaly of SST were prepared for the period May to September for both the years and representative charts depicting the onset and active conditions for 1979 ad 1983 are presented in figures 20 to 23.

Zonal anomalies during 1979:

Figure 20 represents actual onset conditions during 1979 and no significant SST anomaly are present. The weak zonal anomaly observed during June appears to be associated with weak surface winds (Geostationary satellite data) and weak rainfall activity over India. The July conditions (active monsoon conditions, Figure 21) clearly reveal the beginning of upwelling along Somalia and Arabian coasts by negative zonal anomalies in this region, and these features get more pronounced by August. By the beginning of September, these features have already begun to disappear. The maximum negative zonal anomalies of the order of $2^{o}C$ were observed during August in the western Arabian Sea.

Zonal anomalies during 1983:

Figure 22 shows the actual onset conditions during 1983. Strong negative anomalies indicative of intense upwelling off Somali coast can be seen. The negative anomalies become more pronounced by July (active monsoon conditions, figure 23 and the features persist throughout August and September. The maximum negative anomalies of the order of $4^{o}C$ were observed during July off Somalia. Upwelling off Arabian coast was also considerably stronger in 1983 than in 1979.

Our present study is in agreement with the study of Joseph and Pillai (1984) which states that the SST anomalies in the North Indian Ocean influence the monsoon activity over India.

Relationships between SCZASST, CIOZASST and the monsoon rainfall over India:

Studies by Shukla and Misra (1977), Goswami (1983) and Ramesh Babu et al (1985) have shown a positive correlation between SST and monsoon rainfall over different parts of India. In the present study we have chosen two regions which were not studied earlier namely, Somalia coast (4-10^{O}N and 48-52^{O}E) and Central Indian Ocean area (4^{O}S-4^{O}N and 64-84^{O}E) (figure 24), for correlating with the monsoon rainfall over about 15 meteorological subdivisions representing various parts of the country.

We have chosen the SCZASST (Somalia Coast Zonal Anomaly of SST) as the average zonal anomaly between 4^{O}N and 10^{O}N, 48^{O}E and 52^{o}E, for correlating with the monsoon rainfall for the following reasons: It is believed that strong low level winds known as Somali Jet transport significant amount of moisture to the Indian subcontinent. Thus a relationship between the intensity of Somali Jet and monsoon activity over India can be expected to exsist. Shukla and Misra (1977) have obtained a negative correlation between SST and surface winds, idicating that the strong low level winds are associated with low SST's. Saha (1970) had shown the negative correlation between SST and pressure. Thus the existence of strong negative zonal anomalies can be linked to strong surface winds and intense upwelling off Somalia coast. These strong surface winds* can cause intense evaporation over the Arabian Sea. The net effect of the above mentioned factors would be to produce good monsoon over the Indian subcontinent.

We have found out the correlation coefficients between weekly values of SCZASST and the weekly monsoon rainfall of various meteorological subdivisions for the years 1979, 1983 and the combination of both years. Those values which are statistically significant at 95% and 99% level for the combined data (1979+1983) are presented in Table - 6. It is observed that the SCZASST is negatively and significantly correlated with rainfall over western and central parts of India for the same week. The correlation coefficients, in general, were found to decrease when analysed for lags upto three weeks. However, they were still significant for west and east Madhya Pradesh upto lag 1 and lag 3 respectively (95% level).

The CIOZASST (Cenral Indian Ocean Zonal Anomaly of SST) is taken as the average of the zonal anomalies between 4^{O}S and 4^{O}N, 64^{O}E to 84^{O}E. The reason for choosing this area for correlating with monsoon rainfall is as follows. Washington et al (1977) have shown that the SST anomalies in this are under the influence of South Equatorial Trough (SET). Further, studies of Cadet and Olory-Togbe (1981) and Prasad et al (1983) have shown that there exsists a negative correlation between the strengthening of SET activity and monsoon rainfall over India. Table 7 gives the statistically significant correlation coefficients between CIOZASST and monsoon rainfall over different meteorological subdivisions. It is observed that the CIOZASST is positively and significantly correlated with the monsoon rainfall over most of the subdivisions for which SCZASST showed negative correlation.

The source of moisture for summer monsoon rainfall over India:

In an earlier study, Sadhuram and Ramesh Kumar (1988) showed that the cross equatorial flux from the southern hemisphere (SH) contributes to about 70% of the moisture transport across the west coast of India as compared to the evaporation over the Arabian Sea (AS). Some of the salient features of the above study are the following:

a) The rates of evaporation and precipitation during 1979 monsoon are found to balance each other, indicating an insignificant role of evaporation towards moisture transport across the west coast of India.

b) Irrespective of monsoon intensity the ratio of interhemispheric flux to moisture transport across the westcoast of India (i.e., the contribution from the southern boundary wall (Equator) to the eastern boundary (westcoast of India)) has been found to be dominant and consistent on a seasonal scale.

In a recent study, Ramesh Kumar and Sadhuram (1989) have shown that the evaporation over the Arabian Sea during two contrasting monsoon seasons namely 1979 (bad monsoon year) and 1983 (good monsoon year) were of the order of 3.66×10^{10} tons and 3.59×10^{10} tons respectively which has further supported our earlier study (Sadhuram and Ramesh Kumar, 1988).

The present study aims at verifying the above results and examine whether any relationship exists between evaporation over the AS or SH with the monsoon rainfall over India. In addition, the anomaly fields of various parameters like SST, air temperature (AT), wind stress, heat gain over the Ocean (HGO), effective radiation at the surface (ERS) and total heat loss between the good and bad monsoon year composites are also presented.

The rainfall data pertaining to the study was obtained from Shukla (1987) and the years were classified as good and bad if the noramlized rainfall anomaly was more than one standard deviation and less than minus one standard deviation respectively. Thus the years 1953, 1956, 1959, 1961 and 1970 were chosen as good monsoon years and 1951, 1965, 1968 and 1972 were chosen as bad monsoon years for the period from 1948-1972.

Table 8 gives the onset dates and the monsoon rainfall over India for the good and bad monsoon years used in this study. It can be noticed that the onset of summer monsoon along the Kerala coast itself exhibits very large variations (varying from 18 May to 18

June) and the monsoon rainfall also shows large fluctuations, varying from 653.2 mm to 1017.0 mm.

(a) Sea surface temperature :

The SST's were in general relatively higher over the north Indian Ocean excepting the west and east coasts of India during June (figure 25). In the southern Indian Ocean, the values were relatively higher and maximum positive anomalies were observed in the MSQ's 400 and 401. In July, SST anomalies off the coasts of Somalia and Arabia were negative indicating active monsoon conditions. Maximum positive anomalies were observed in the MSQ's 328 and 329 in August. By September, the entire north Indian Ocean showed negative anomalies with maximum values off Somalia and Arabia showing the effect of strong monsoonal cooling. Earlier studies of Ramesh Kumar et al., (1986a) and Joseph and Pillai (1986) have reported similiar features for other years(1979, 1983 and 1972 and 1973).

(b) Air temperature :

The air temperature in general followed the SST pattern. Maximum positive anomaly is observed in June in the MSQ 401 (figure 26). The small positive air temperature anomalies in the north Indian Ocean turned into negative anomalies with the effect of strong monsoonal cooling, especially off the coasts of Arabia, Somalia and the west coast of India.

(c) Wind stress :

The wind stress anomalies were in general positive over the whole Indian Ocean except over a few locations like the Arabian coast in June (figure 27). This picture underwent a dramatic change with the establishment of active monsoonal circulation in the month of July, with large areas of negative anomalies especially in the belt $10^{o}S - 20^{o}S$. In the month of August, the relatively large positive anomalies were observed in the western Indian Ocean as compared to the eastern Indian Ocean indicating strong cross equatorial flow during good monsoon years. Thus, it can be concluded that winds in the month of August play a vital role in moisture transport across the equator, which is the month when the maximum break in monsoon conditions occur over India.

(d) Effective radiation at the surface (E.R.S):

Figure 28 presents the net radiation anomalies between the good monsoon composites for the Indian Ocean. An interesting feature is that the net radiation is in general more during bad monsoon years as compared to the good monsoon years, which may be due to the effect of lesser cloudiness, over the oceanic regions. The maximum anomalies were observed in the north Indian Ocean in the month of August as comapared to the other monsoonal months.

(e) Heat gain over the Ocean (H.G.O) :

The central AS and the west coast of India (represented by MSQ'S 66 and 65 respectively) exhibited negative anomalies throughout the season with the maximum values in September (Figure 29). The east coast of India (represented by MSQ 64) undergoes drastic variations with the positive anomaly values decreasing by about 63 Wm^{-2} from June to July. Maximum variation occurs in the period from July to August when it changes from 49 Wm^{-2} to -72 Wm^{-2}. These large variations over this area within these four months can mainly be attributed to the monsoon depressions, which form during this period (June to September).

(f) Total heat loss (L.H.F + S.H.F) :

Figure 30 presents the total heat loss over the study area. The north Indian ocean exhibits a complex picture with some areas showing positive anomalies and other areas exhibiting negative anomalies. An interesting feature of this region is that the central Arabian sea exhibits positive anomaly throughout the monsoon season with the minimum value in August and maximum value in September. The Arabian and Somalia coasts exhibit large negative anomalies once the monsoonal circulation is established over the AS (ie., from July onwards). These negative anomalies can be due to the strong cross equatorial flow (namely Somali low level Jet) which in turn can cause intense upwelling along these coasts.

Due to the intense upwelling off the Somalia and Arabia coasts, there exists large air-sea temperature differences. The S.H.F values are negative because $T_s - T_a$ values are negative. And, the S.H.F values are also relatively higher during a good monsoon composite than a bad one because of intensity of upwelling is more during a good monsoon composite than a bad one. The L.H.F values are more or less equal during both the composites. Thus, the total heat loss (i.e., L.H.F + S.H.F) is less during a good monsoon composite than the bad one and hence the negative anomalies off Somalia and Arabia coasts.

Tables 9a & 9b give the evaporation rates over the Arabian Sea (AS) and Southern Hemisphere (SH) respectively. From Table 9a it can be seen that the evaporation values over the AS show a gradual decrease with the onset of summer monsoon with the lowest values observed in September irrespective of good or bad monsoon conditions over the Indian subcontinent. Another interesting feature that can be observed is that the evaporation values are relatively higher in June and July during good monsoon composite than the bad one. The reverse is true for the months August and September. If we consider the season as a whole, there is hardly any difference between the good and bad monsoon composite values. This was already reported earlier by Ramesh Kumar and Sadhuram (1989) for 1979 (bad monsoon year) and 1983 (good monsoon year).

Table 9b gives the evaporation rates for the SH. The evaporation rates over SH were found to decrease with the progress of the southwest monsoon. A comparison of tables 9a and 9b shows that the evaporation rates are in general more over the SH than in the AS during all the months irrespective of good or bad monsoon conditions over India. Another interesting feature of table 9b is that the evaporation rates during a bad monsoon composite shows drastic reduction from July to September, whereas for a good monsoon composite the evaporation rates show only a slight increase from July to August and then a decrease from August to September.

Table 10 gives the interannual variation of evaporation rates for the AS and SH. It is seen that there are both large interannual and intraseasonal variations in the evaporation rates. An important feature is that the evaporation over the SH are always greater than the AS especially for August (almost twice that of the AS value) and September. Thus it looks as if the moisture from the southern hemisphere plays a crucial role in the monsoon activity over India, especially in August and September. This is important as it is in the month of August that the maximum break in monsoon conditions over India is observed.

The mean moisture flux across the boundary wall between AS and SH for 1964 (normal), 1975 (good) and 1979 (bad) monsoon years is given in Table 11. It is seen that the mean cross equatorial flux across the boundary wall varies from year to year and with the maximum moisture flux transport into the AS during a good monsoon (almost twice that of a bad monsoon year).

TABLE - 5

Relationship between the appearence of the 27°C isotherm off the Somali coast and the advance of the Northern Limit of Monsoon/Southwest monsoon over Kerala.

Year	Week in which the 27°C isotherm appears off Somali coast in GOSSTCOMP chart.	Advance of Northern Limit of of Monsoon/Southwest Monsoon over Kerala
1979	12th June	11th June
1981	2nd June	30th May
1982	1st June	30th May
1983	14th June	13th JUne

The date referred to in the GOSSTCOMP chart is the middle day of that particular week.

TABLE - 6

Statistically significant correlation coefficients (95 and 99% level) between SCZASST and weekly subdivisional monsoon rainfall over India for 1979 and 1983 (combined analysis).

Subdivision	1979+1983			
	0	1	2	3
Kerala	----	----	----	-0.565*
Konkan & Goa	-0.551*	----	----	----
West Rajasthan	-0.421*	----	----	----
East Rajasthan	-0.559*	----	----	----
West Madhya Pradesh	-0.602*	-0.454	----	----
East Madhya Pradesh	-0.635*	-0.545*	-0.477*	-0.381
Marthawada	----	----	-0.444	----
Vidarbha	-0.537*	----	----	----
Coastal Andhra Pradesh	----	----	-0.440	----

* Refers to the correlation coefficients which are significant at 99% confidence level. There are 15 data samples each in 1979 and 1983.

TABLE - 7

Statistically significant correlation coefficients (95 and 99% level) between CIOZASST and weekly subdivisional monsoon rainfall over India for 1979 and 1983 (combined analysis).

Subdivision	0	1	2	3
Kerala	0.431	----	----	----
Konkan & Goa	0.543*	0.378	----	----
East Rajasthan	0.435	----	----	----
West Madhya Pradesh	0.634*	0.486*	----	----
East Madhya Pradesh	0.660*	0.519*	----	----
Marathwada	0.507*	0.472*	----	----
Vidarbha	0.558*	0.521*	----	----
Coastal Andhra Pradesh	----	----	----	-0.538*

* Refers to the correlation coefficients which are significant at 99% confidence level. There are 15 data samples each in 1979 and 1983.

TABLE 8

Dates of onset of summer monsoon over the Kerala coast, the southern most part of India, for the good and bad monsoon years along with the monsoon rainfall over India. * refers to the bad monsoon years. (Source: Shukla, 1987).

Year	Date	Monsoon rainfall (mm)
1951*	31 May	736.9
1953	07 June	919.7
1956	21 May	979.5
1959	31 May	938.1
1961	18 May	1017.0
1965*	26 May	706.8
1968*	08 June	753.7
1970	26 May	939.4
1972*	18 June	653.2

TABLE 9a

Evaporation rates over the Arabian sea (Area A)

Units: 10^{10} tons/day.

Month	Bad composite B	Good composite G	Mean	Difference (G-B)
June	3.01	3.28	3.15	0.27
July	2.74	2.79	2.77	0.05
August	2.36	2.12	2.24	-0.24
September	1.82	1.72	1.77	-0.10
Mean for the season	2.48	2.48	2.48	0.00

TABLE 9b

Evaporation rates over the southern hemisphere (Area B)

Units: 10^{10} tons/day.

Month	Bad composite B	Good composite G	Mean	Difference (G-B)
June	5.14	4.96	5.04	-0.18
July	5.21	4.60	4.91	-0.61
August	4.47	4.88	4.67	0.41
September	3.57	3.14	3.36	-0.43
Mean for the season	4.60	4.40	4.50	-0.20

TABLE 10

Evaporation rates for Arabian sea (open) and southern hemisphere (within brackets). Units: 10^{10} tons/day.

Year/Month	June	July	August	September	Seasonal mean	Seasonal difference
1951	3.15	2.28	1.64	1.40	2.12	1.79
	(4.35)	(4.85)	(3.56)	(2.89)	(3.91)	
1953	3.43	2.78	1.83	1.63	2.42	1.19
	(3.70)	(3.99)	(3.75)	(3.03)	(3.61)	
1956	3.00	2.72	1.39	1.83	2.23	1.92
	(4.96)	(5.04)	(4.70)	(1.90)	(4.15)	
1959	3.00	2.68	2.31	1.27	2.32	1.32
	(3.67)	(3.82)	(3.93)	(3.14)	(3.64)	
1961	4.02	3.23	2.30	1.83	2.84	1.95
	(6.14)	(5.26)	(4.83)	(2.92)	(4.79)	
1965	2.82	2.82	2.30	1.69	2.41	1.86
	(4.22)	(4.40)	(4.77)	(3.66)	(4.27)	
1968	2.28	2.97	1.91	1.98	2.29	2.81
	(5.11)	(6.04)	(4.99)	(4.28)	(5.10)	
1970	2.96	2.55	2.79	2.22	2.63	3.08
	(5.86)	(5.30)	(6.81)	(4.87)	(5.71)	
1972	3.79	2.89	3.31	2.29	3.07	1.90
	(6.83)	(5.49)	(4.44)	(3.13)	(4.97)	
Mean	3.16	2.77	2.20	1.79	2.48	1.98
	(4.98)	(4.91)	(4.64)	(3.31)	(4.46)	

TABLE 4.11

Moisture flux across the boundary wall between Arabian sea (Area A) and Southern hemisphere (Area B) for normal (1964), good (1975) and bad (1979) monsoon years. (the -ve values indicate inward flux into the Area A). Units : 10^{10} tons/day

Month/Year	1964	1975	1979	Mean
June	-3.38	-6.90	-3.23	-4.50
July	-4.36	-5.80	-2.99	-4.38
August	-3.89	-5.80	-2.71	-4.13
September	-3.01	-5.30	-1.46	-3.26
Mean	-3.66	-5.95	-2.60	-4.07

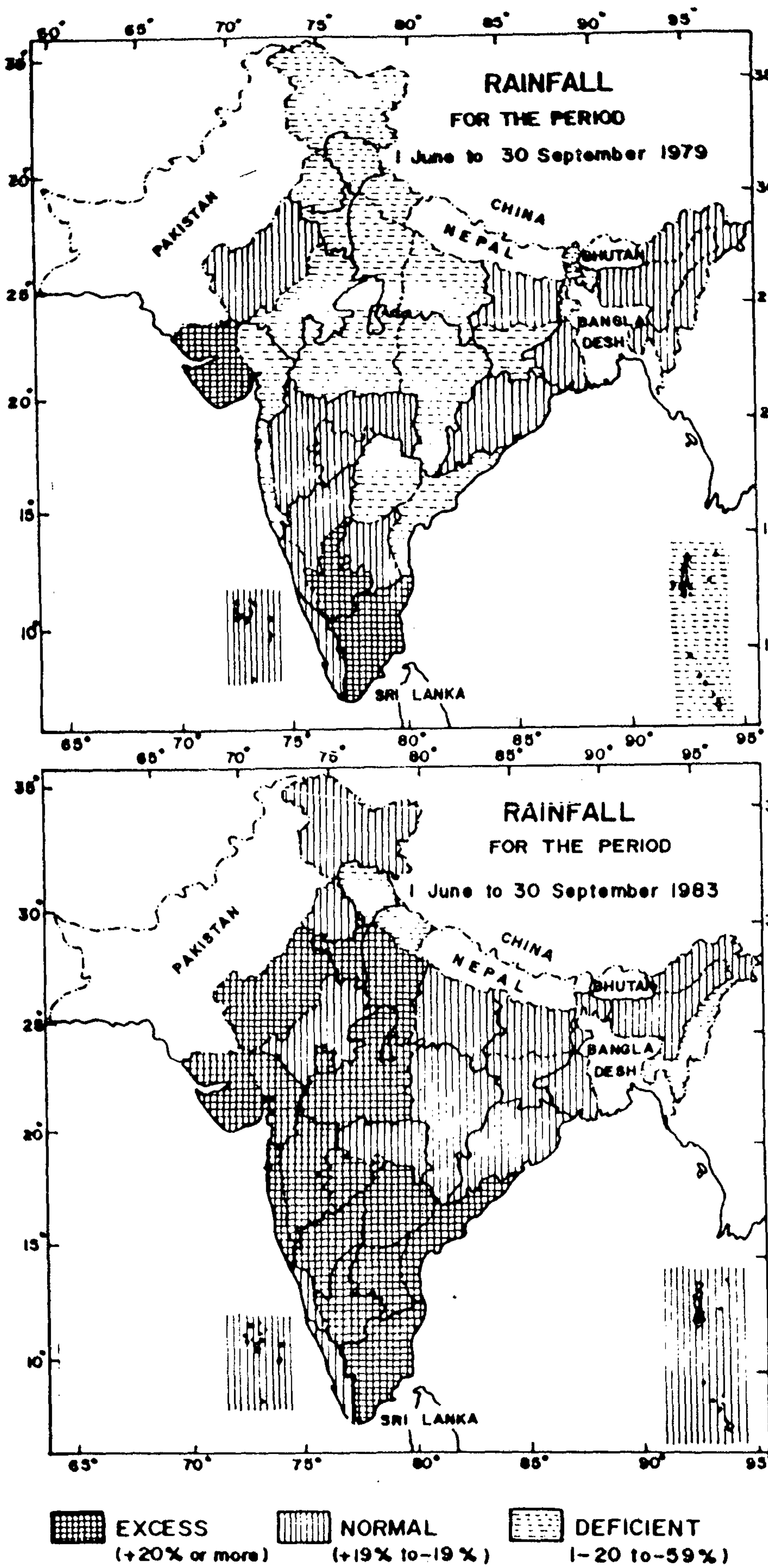


Fig. 17 DEPARTURE FROM NORMAL OF MONSOON RAINFALL (1 JUNE TO 30 SEPTEMBER) OF SUB-DIVISIONS OF INDIA FOR THE YEARS 1979 AND 1983

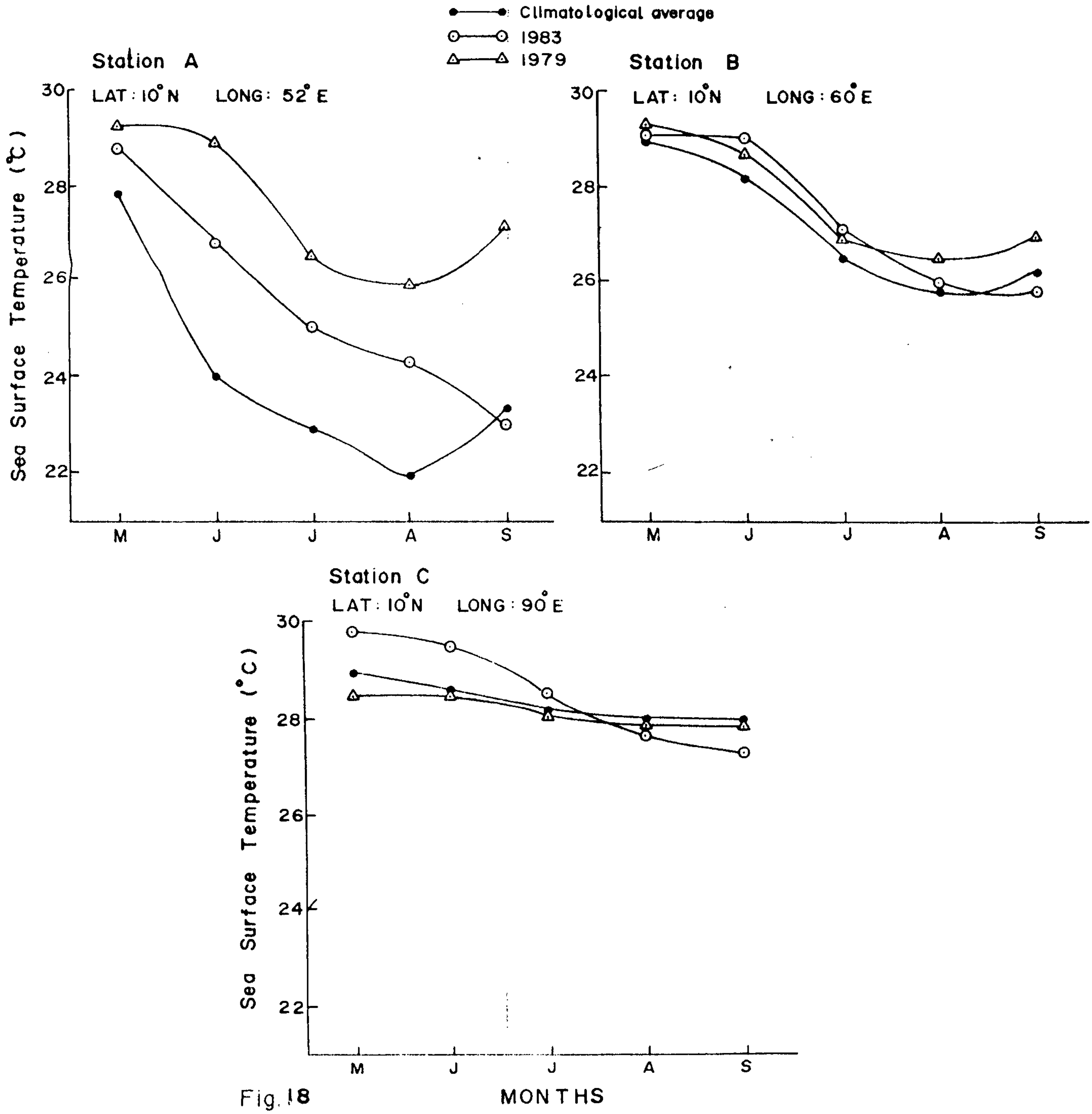
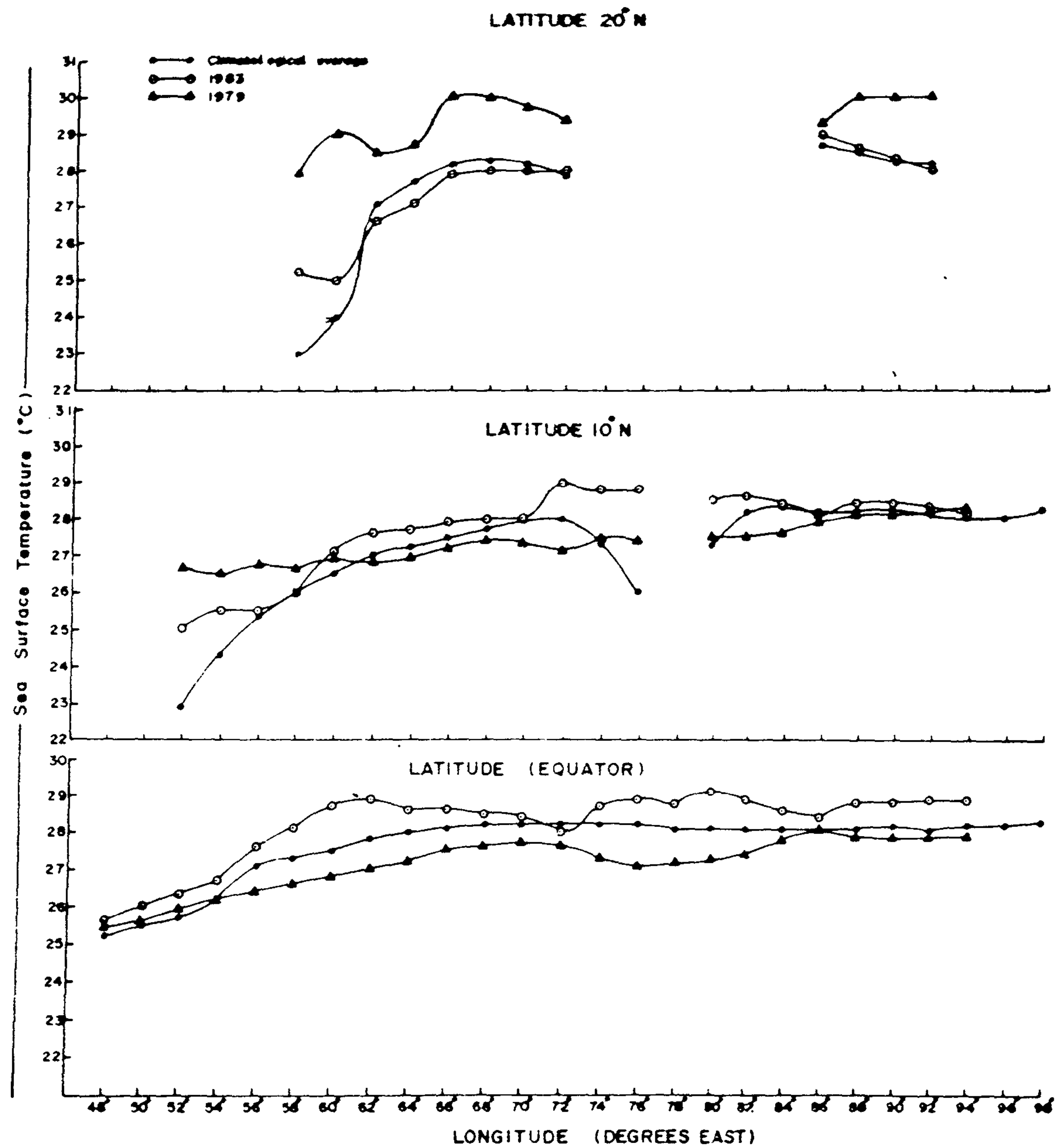


Fig. 18

VARIATION OF MONTHLY MEAN SST (°C)



LONGITUDINAL VARIATION OF MEAN JULY SST

Fig. 19

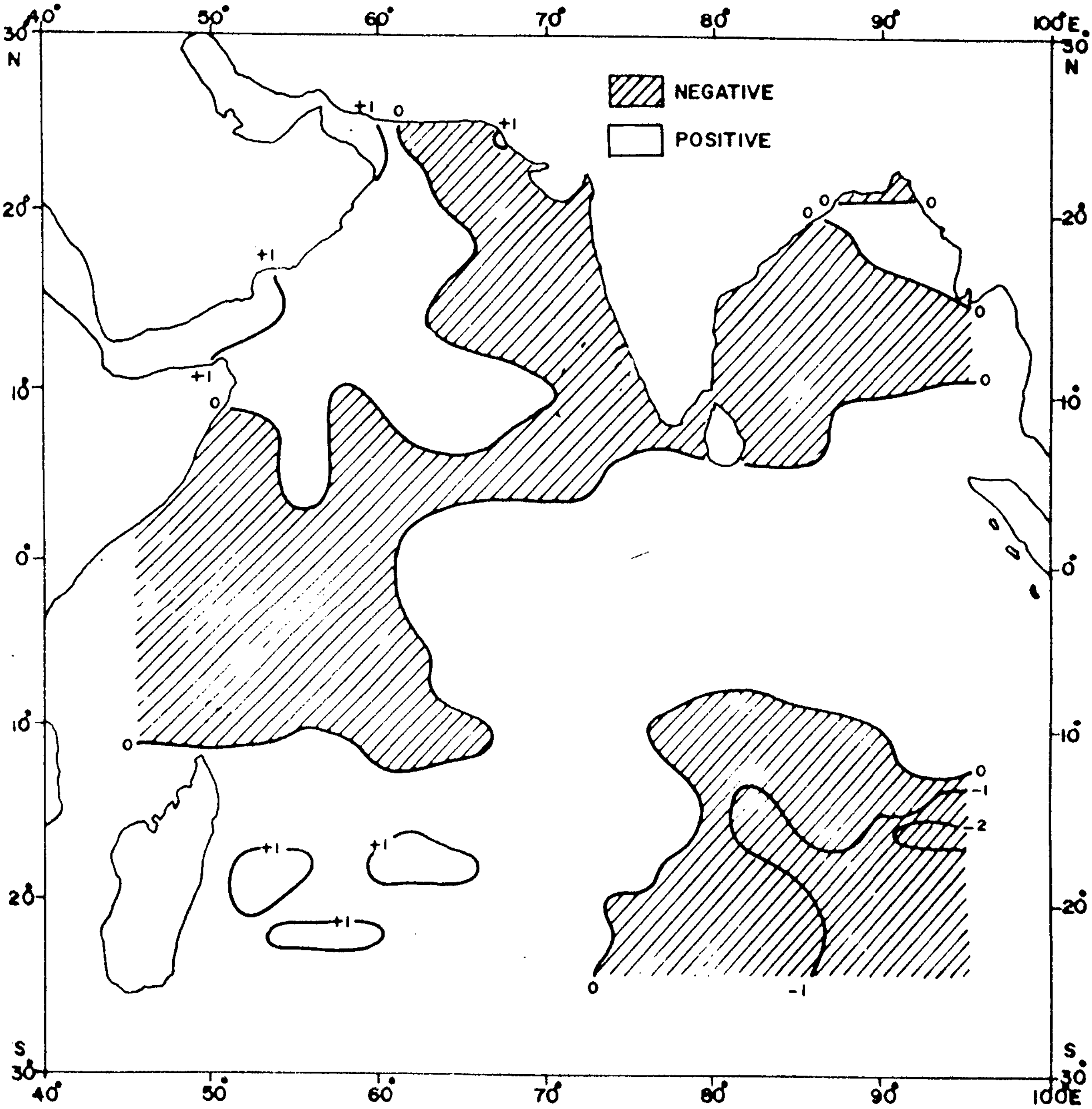


Fig.20[1]. ZONAL ANOMALY OF SST DISTRIBUTION ON 12-6-1979

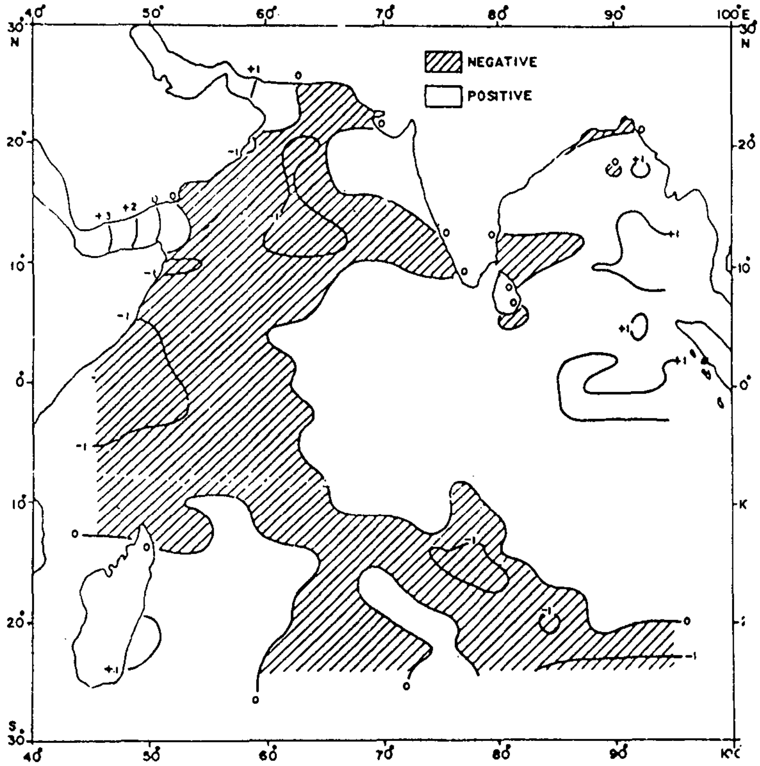


Figure 21. Zonal anomaly chart of SST depicting the active monsoon conditions (24 July 1979)

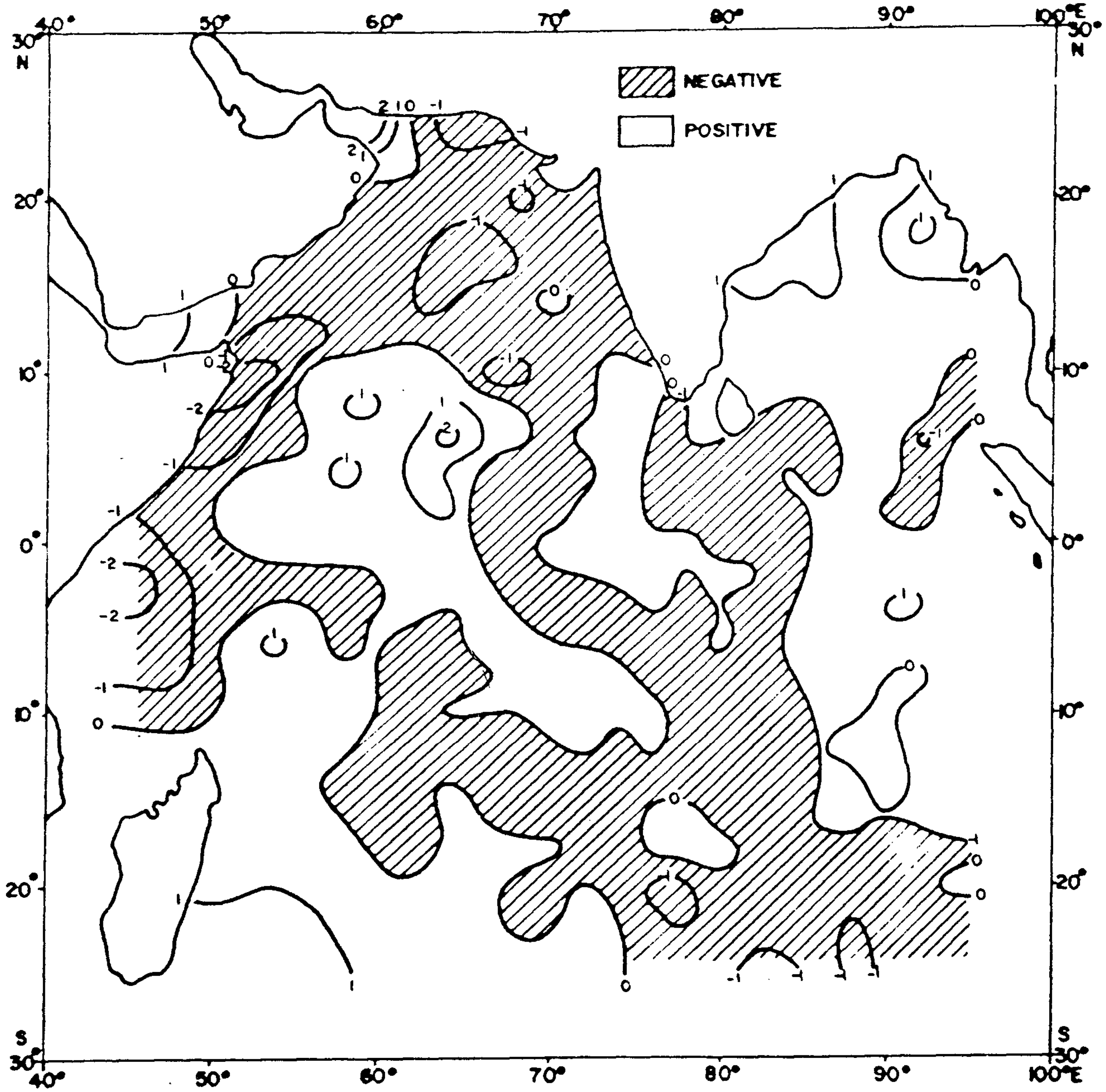
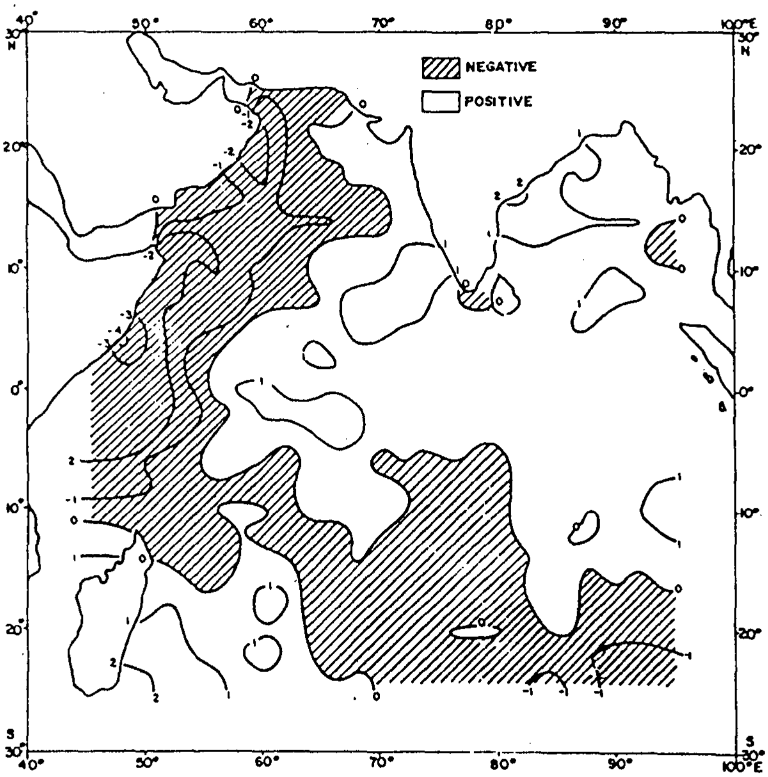


Fig. 2.2. ZONAL ANOMALY OF SST DISTRIBUTION ON 14-6-1983



23

Figure [illegible]. Zonal anomaly chart of SST depicting the active monsoon conditions (19 July 1983). The chart also indicates pronounced upwelling off Somali and Arabian coasts as compared to the year 1979.

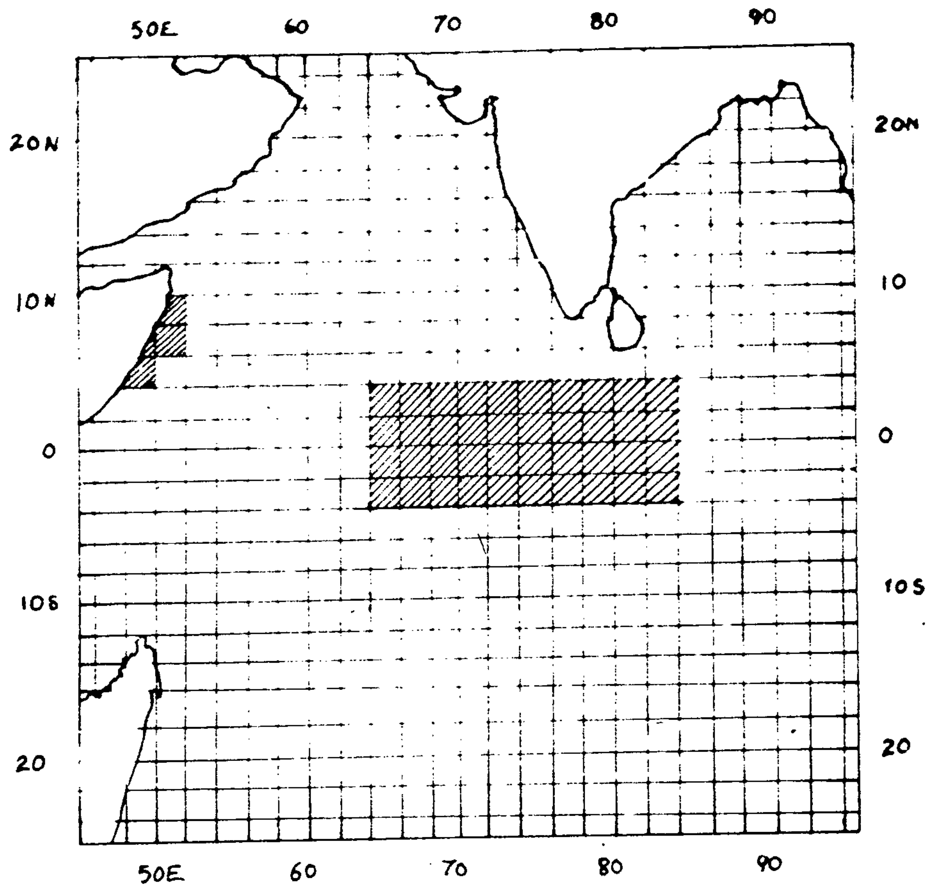


Fig.24 MAP SHOWING THE STUDY AREAS USED FOR CORRELATING ZONAL ANOMALY OF SST WITH MONSOON RAINFALL.

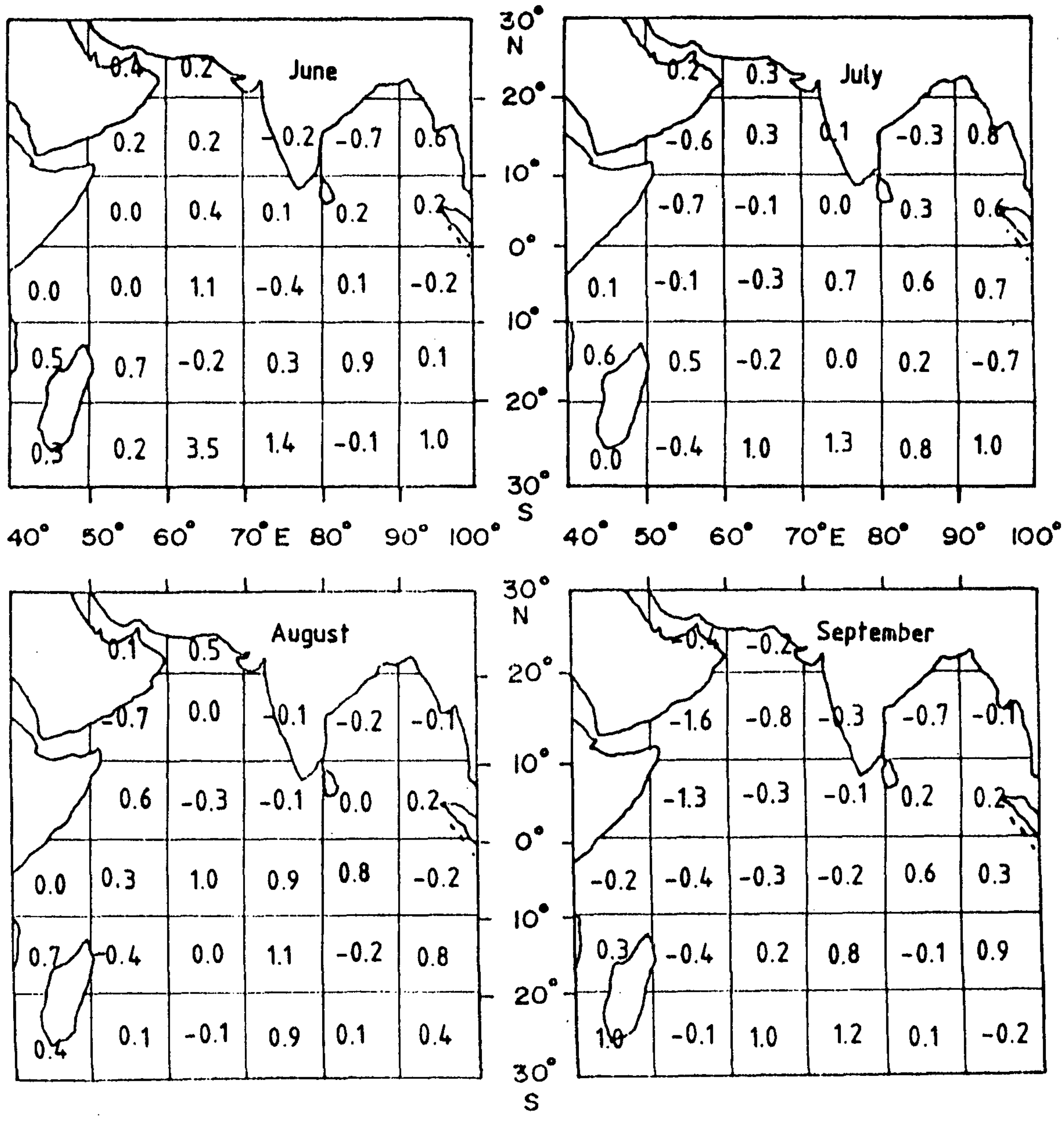


Fig. 25

Sea surface temperature anomalies (°C) between good and bad monsoon composites.

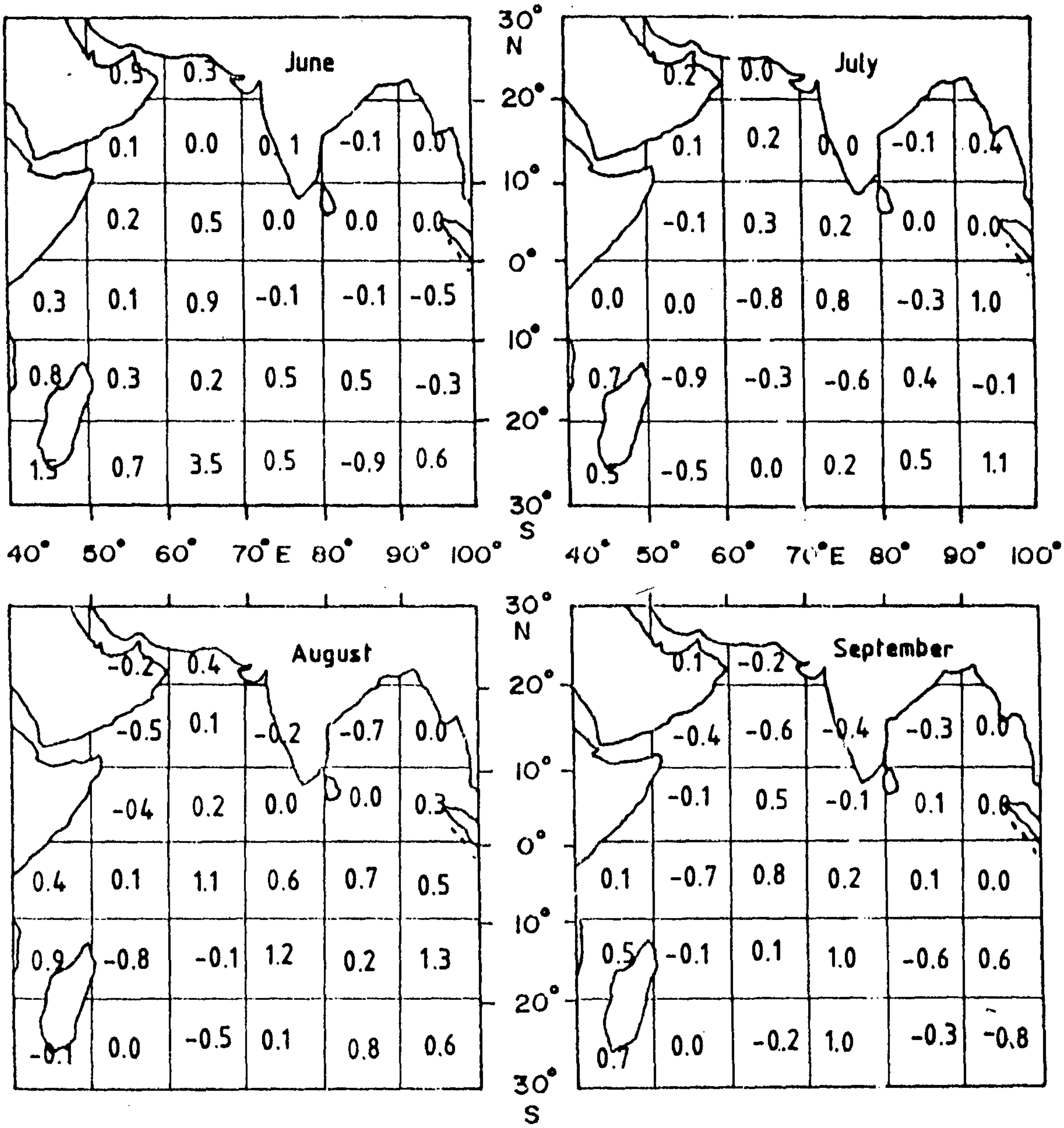


Fig. 26

Air temperature anomalies (°C) between good and bad monsoon composites.

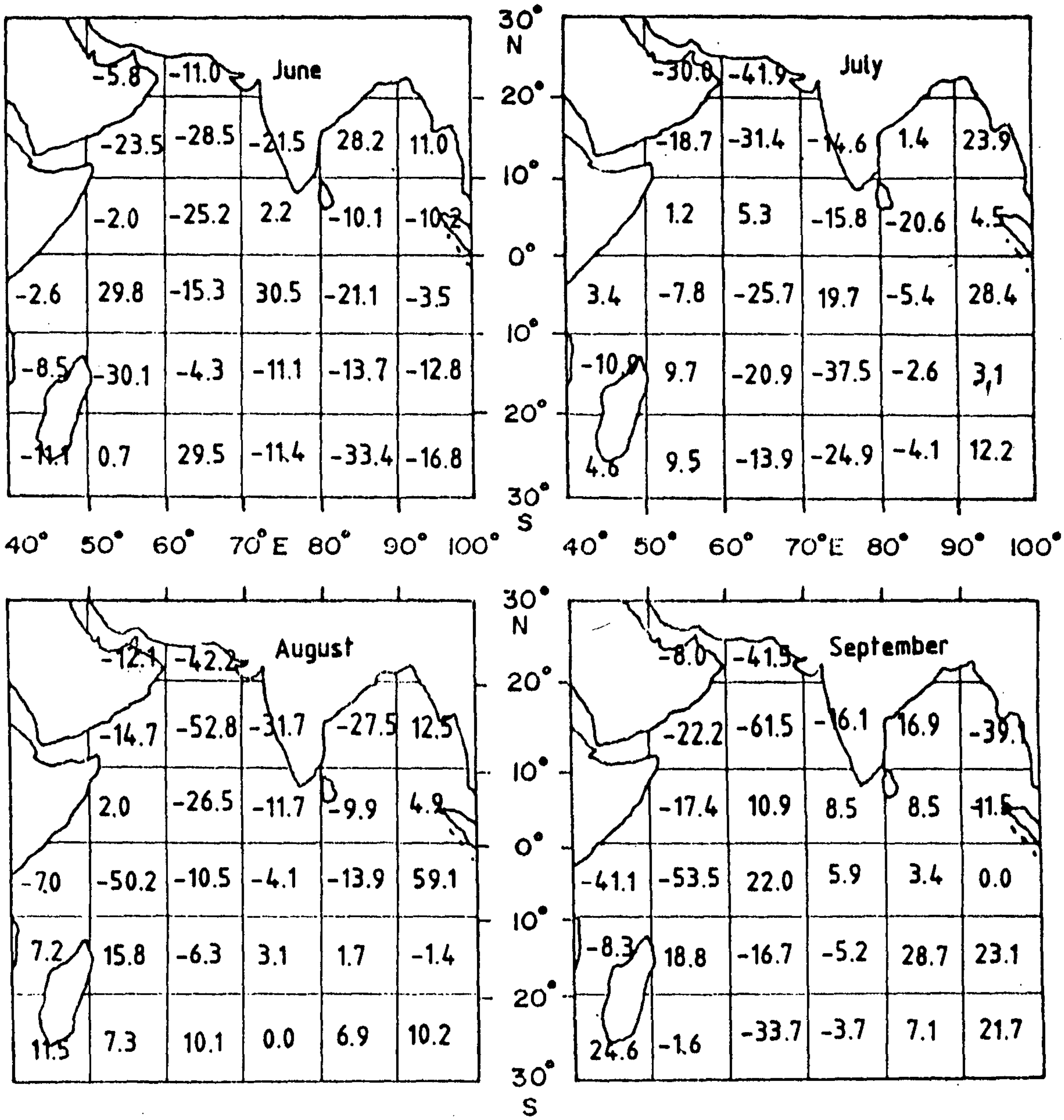


Fig. 28

E.R.S. anomalies (w/m^2) between good and bad monsoon composites.

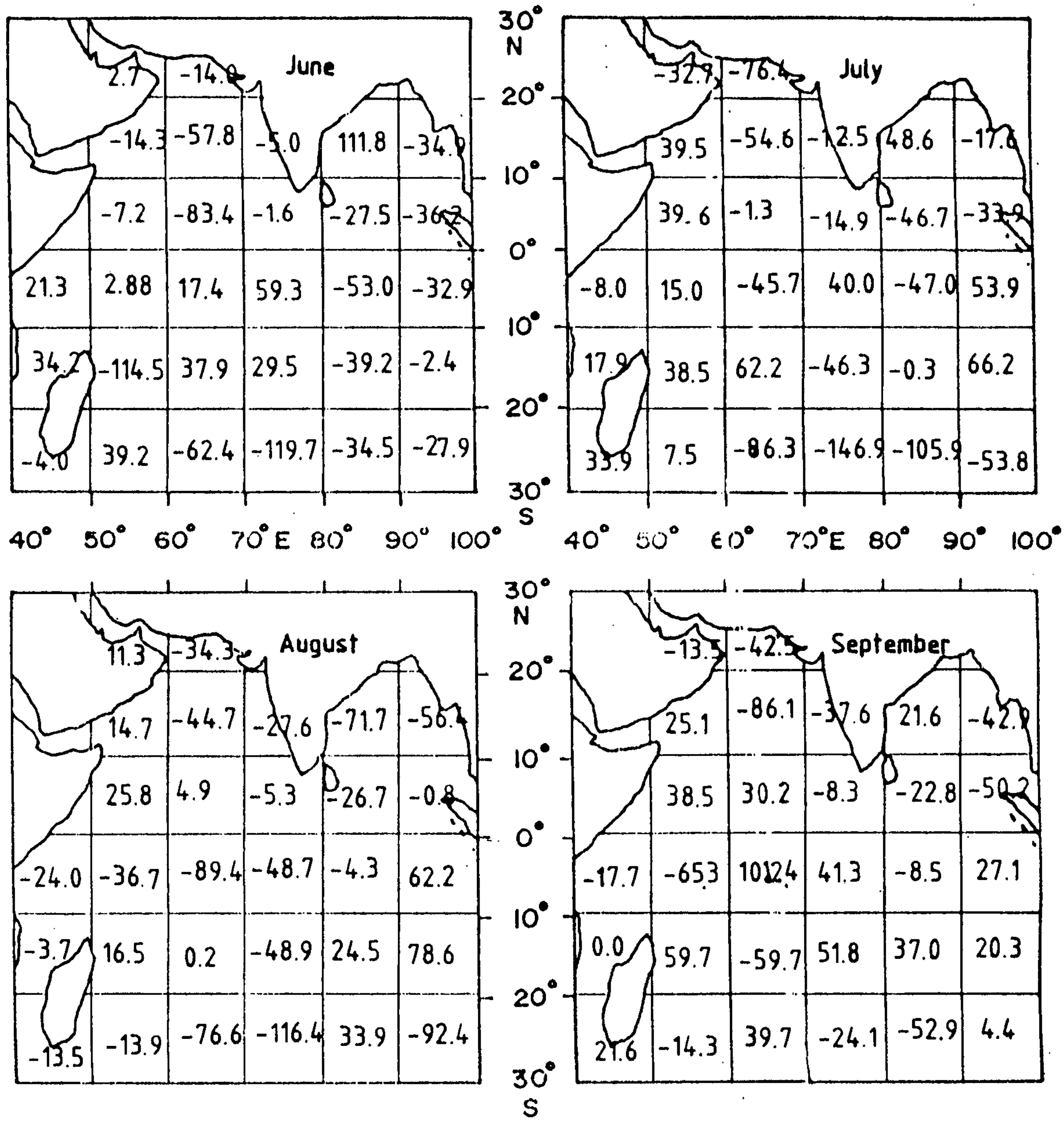


Fig. 29

H.G.O. anomalies (w/m^2) between good and bad monsoon composites

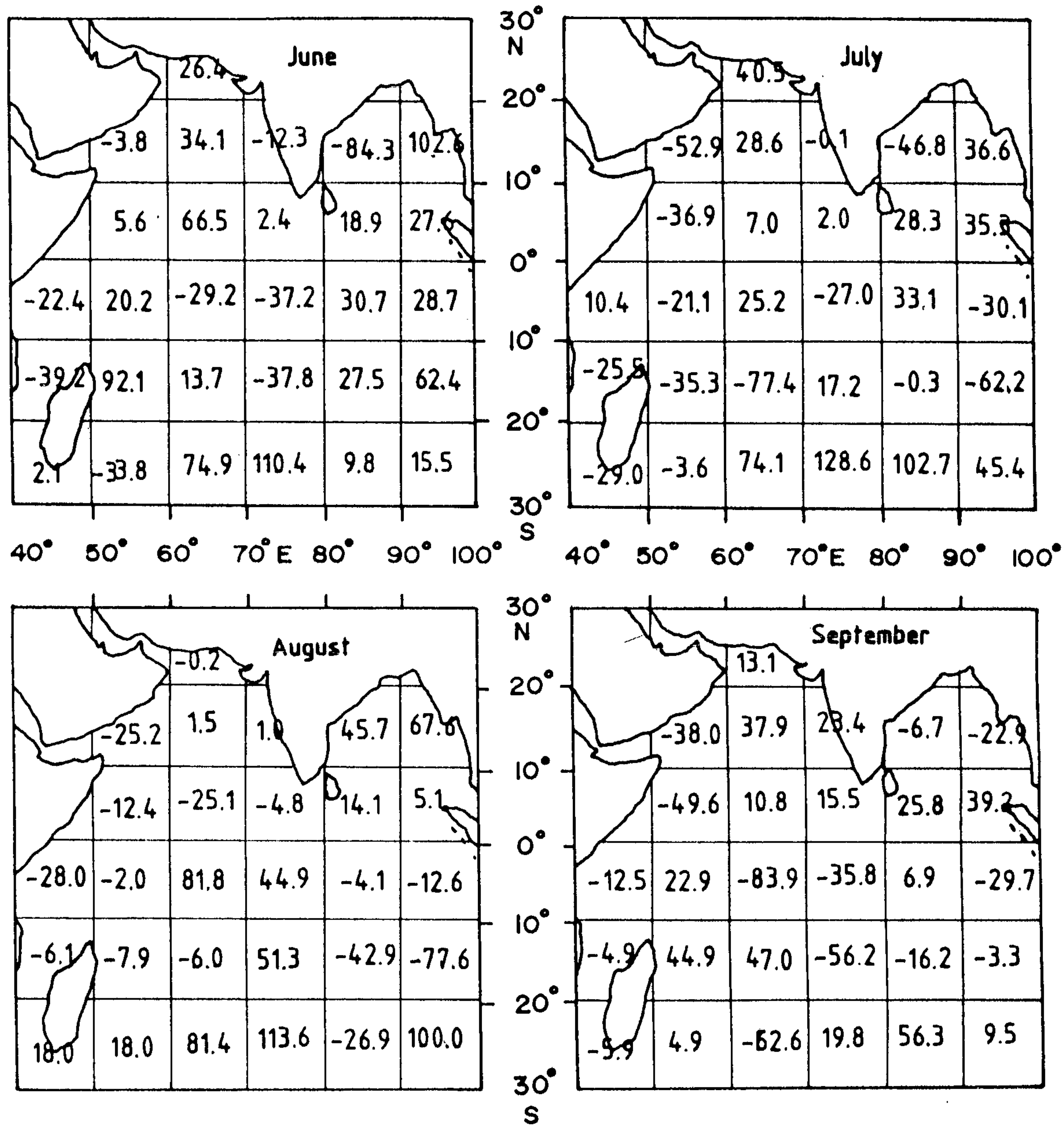


Fig. 30

Total heat loss anomalies (w/m^2) between good and bad monsoon composites.

CHAPTER V

SEA SURFACE TEMPERATURE ANOMALIES IN THE ARABIAN SEA

Several authors (Shukla, 1975; Washington et al., 1977; Druyan et al., 1983; Cadet and Diehl, 1984; Joseph and Pillai, 1986; Ramesh Kumar et al 1986; Ramesh Kumar and Sadhuram, 1989) have shown that the SST anomalies over the Arabian Sea (AS)/Indian Ocean modify the monsoonal circulation and hence the summer monsoon rainfall over the Indian subcontinent. The exact nature how these anomalies affect the monsoon circulation has been a controversial topic. The nature of the SST anomalies, their causative factors, duration and amplitude and how they are related to other surface meteorological parameters and surface fluxes, are examined in the present article.

In this study, the anomalies over the northern, western, central, eastern and southern Arabian Sea represented by MSQ's 102, 67, 66, 65 and 29 (Figure 1) are examined. The reason for choosing the above squares have been mainly the data density and uniform distribution wihin the study period (1948-1972). In addition, we present the scatter plots of sea surface temperature anomalies (SSTA) for the different study areas and their relarionship with different meteorological parameters and air-sea fluxes are examined.

The method for computing the various anomalies in brief is as follows: The monthly mean total of various parameters like SST, wind stress, HGO and the ERS were computed first. Then the monthly means were computed for each of the 12 months (from January to

December). Then the anomalies were computed for each individual case for a given period (for example between 1 and 2 months) and compared with the other anomalies for consistency or non consistency to find the causative factor. The details of the program used for computing the various anomalies and their causative factors are given in ANNEXURE A.

In the case of the northern AS (figure 31), there are about 104 SSTA's during the study period. Figure 31a gives the scatter plot of amplitude Vs period of the anomalies. From the figure it can be seen that most of the anoamlies lie within the temperature range of $-0.6^{\circ}C$ to $0.6^{\circ}C$ and with periods less than five months. Only about 12 anomalies exist outside the above temperature and period range. Figure 31b shows that most of the anomalies (about 46) are of one month duration. The seasonal anomalies (i.e., anomalies with duration greater than three months) are only 45. The amplitudes of the anomalies are in general less and there are equal number of positive and negative anomalies, with the maximum number lying in the range 0.0 to $0.2^{\circ}C$ (figure 31c).

Table 12 shows that most of the short duration anomalies (of periods less than 4 months) are driven by the surface heat fluxes. The larger duration anomalies (of periods greater than 4 months) are driven by advection (both horizontal and vertical) and other oceanic processes. In the case of very long duration anomalies (of periods greater than 10 months), the reasons were not clear as to what causes these anomalies and maintains them.

There are about 93 anomalies for the western AS area (Figure 32a). About one third of these anomalies were of one month duration and about 75% of these anomalies were with periods less than 5 months (Figure 32b). The maximum number of anomalies, about 13 in number, lie in the range $-0.6^{\circ}C$ and $-0.8^{\circ}C$.(Figure 32c), unlike the previous study area where most of the anomalies were confined within the range 0.0 *^{o}C to $0.2^{\circ}C$.

An analysis of the statistics of the various causative factors (Table 13) shows that about 42 anomalies are lying in the period range 1-2 months and are driven by the surface heat fluxes, where as in the case of anomalies with periods greater than two months it is the advection (horizontal and vertical) and other oceanic processes which play a major role in their formation and maintainence.

The scatter plot of SSTA for the central AS area is shown in figure 33a. There are about 90 anomalies in the central AS area. Here also the short duration anomalies (of one month duration) are greater in number than other anomalies and almost 75% of the total anomalies lie in the period range of less than 5 months (Figure 33b). The anomalies exhibit a normal distribution with most anomalies conifined to the temperature range $-0.8^{\circ}C$ to $0.8^{\circ}C$ (Figure 33c).

The percentage wise distribution of the anomalies for different durations and their causative factors for the central AS are presented in Table 14. Most of the short duration anomalies (with periods less than 5 months) are driven by the surface heat fluxes. The medium period anomalies (i.e., anomalies greater than 5 months) are driven by advection and other oceanic processes.

Figure 34a shows a wide scatter of the SSTA's for the eastern AS area. The maximum number of anomalies about 42 in number are having periods less than two months (Figure 34b) and their numbers decrease with increasing periods. The amplitude of the various anomalies for the eastern AS, are depicted in figure 34c.

An analyis of the anomalies in different period groups and their causative factor in percentages for the area MSQ 65, shows that about 75% of the anomalies lie in the range 1-2 month period (Table 15). The causative factor for the short duration anomalies (i.e., periods less than 5 months) are the surface heat fluxes. In the case of large duration anomalies the causative factors are advection and other oceanic processes.

A high scatter in the SSTA's over the southern AS area is observed (Figure 35a). Figure 35b shows that most of these anomalies are of one to two months duration and they contribute to about 60% of the total anomalies and the maximum number of anomalies (about 18 in number) lie in the range $-0.2^{\circ}C$ and $-0.4^{\circ}C$ (figure 35c).

The analysis of SSTA's (Table 16) shows that the short duration anomalies (with periods less than 2 months) are driven by the surface heat fluxes, for the southern AS. In the case of medium period anomalies (i.e, anomalies with periods lying between 3 and 4 months) the things are not clear as to what causes these anomalies and what maintains them so is the case of anomalies with periods lying in the range 7-8 months duration. Other anomalies are driven by the advection (both horizontal and vertical) and other oceanic processes.

In order to check whether any causal relationship exist between the various surface meteorological parameters and the air-sea fluxes for the above study areas with SSTA's for period 1948 to 1972, the correlation coefficients between them were computed and are presented in Table 17. From the table it is clear that the SSTA's are positively and significantly correlated with the anomalies of air temperature and latent heat flux values (at 99.9% and 99.0% confidence levels) and also negatively and significantly with the heat gain anomalies for all the study areas except northern AS. It was also noticed that the anomalies of net radiation and wind stress are weakly correlated with the SSTA's showing that the effect of these on the SSTA's is minimal, except over the northern AS area where the net radiation values are negatively and significantly correlated with the SSTA's.

Thus our present results are in agreement with the study of Sarchik (1978) who has suggested using a one dimensional coupled Ocean Atmosphere model that the SST is relatively insensitive to changes in the solar constant, the additional solar flux being compensated by additional evaporation. The results of the present study are in also agreement with the study of Shetye (1986) who suggested that the AS seasonal cycle of SST can be modelled using the Kraus -Turner thermodynamics alone for the nine month period and for the southwest monsoon period the dynamics also played a vital role. The present study also conforms to his findings in that, that most of the short duration anomalies are driven by the air-sea fluxes. The medium and large duration SST anomalies are generally caused by the effect of monsoon circulation (Joseph, 1983; Ramesh Kumar and Sastry, 1990), or the advection process (both horizontal and vertical processes) and other oceanic processes.

The results of the present study are to be used with certain amount of caution because

a) We have used indirect methods for computing causative factors for SST anomalies.
b) The values of the various fluxes computed are dependent upon a number of coefficients whose accurate values are not known.

TABLE 12

Sea surface temperature anomalies*, their periods and causative factors for the northern Arabian sea (MSQ 102)

Period in months / Causative Factor (%)	1-2	3-4	5-6	7-8	9-10	10-11
Total anomalies	059	027	011	005	----	----
S.H.F	044.1	037.0	036.4	020.0	----	----
Advection	025.4	033.3	045.5	040.0	----	----
N.C	030.5	029.6	018.2	040.0	----	----

* SST anomalies less than 5 in number are not presented. S.H.F stands for Surface heat flux, Advection stands for both horizontal and vertical advection and other oceanic processes and N.C stands for not clear situations.

TABLE 13

Sea surface temperature anomalies*, their periods and causative factors for the western Arabian sea (MSQ 67)

Period in months / Causative Factor (%)	1-2	3-4	5-6	7-8	9-10	10-11
Total anomalies	043	027	013	----	----	----
S.H.F	041.9	044.4	015.4	----	----	----
Advection	032.6	048.1	053.8	----	----	----
N.C	025.6	007.4	030.8	----	----	----

* SST anomalies less than 5 in number not presented. S.H.F stands for Surface heat flux, Advection stands for both horizontal and vertical advection and other oceanic processes and N.C stands for not clear situations.

TABLE 14

Sea surface temperature anomalies*, their periods and causative factors for the central Arabian Sea (MSQ 66)

Period in months / Causative Factor (%)	1-2	3-4	5-6	7-8	9-10	10-11
Total anomalies	052	017	013	----	----	----
S.H.F	038.5	052.9	015.4	----	----	----
Advection	030.8	023.5	053.8	----	----	----
N.C	030.8	023.5	030.8	----	----	----

* SST anomalies less than 5 in number not presented. S.H.F stands for Surface heat flux, Advection stands for both horizontal and vertical advection and other oceanic processes and N.C stands for not clear situations.

TABLE 15

Sea surface temperature anomalies*, their periods and causative factors for the eastern Arabian Sea (MSQ 65)

Period in months / Causative Factor (%)	1-2	3-4	5-6	7-8	9-10	10-11
Total anomalies	042	014	007	----	----	----
S.H.F	038.1	050.0	028.6	----	----	----
Advection	031.0	028.6	042.9	----	----	----
N.C	031.0	021.4	028.6	----	----	----

* SST anomalies less than 5 in number not presented. S.H.F stands for Surface heat flux, Advection stands for both horizontal and vertical advection and other oceanic processes and N.C stands for not clear situations.

TABLE 16

Sea surface temperature anomalies*, their periods and causative factors for the southern Arabian Sea (MSQ 29)

Period in months / Causative Factor (%)	1-2	3-4	5-6	7-8	9-10	10-11
Total anomalies	051	016	007	----	006	----
S.H.F	035.3	025.0	042.9	----	000.0	----
Advection	033.3	031.3	042.9	----	066.7	----
N.C	031.4	043.8	014.3	----	033.3	----

* SST anomalies less than 5 in number not presented. S.H.F stands for Surface heat flux, Advection stands for both horizontal and vertical advection and other oceanic processes and N.C stands for not clear situations.

TABLE 17

Correlation between the SSTA's and the surface meteorological parameters and air-sea fluxes for different study areas

Parameter	MSQ 102	MSQ 067	MSQ 066	MSQ 065	MSQ 029
T_a	0.77^1	0.67^1	0.64^1	0.57^1	0.58^1
L.H.F	0.25	0.36^1	0.27^2	0.37^1	0.32^2
H.G.O	-0.20	-0.38^1	-0.28^2	-0.35^1	-0.32^2
t	0.18	0.09	0.04	0.10	-0.05
R	-0.32^2	0.04	-0.07	-0.02	-0.09

where 1 and 2 stands for correlation coefficients significant at 99.9% and 99.0% respectively.

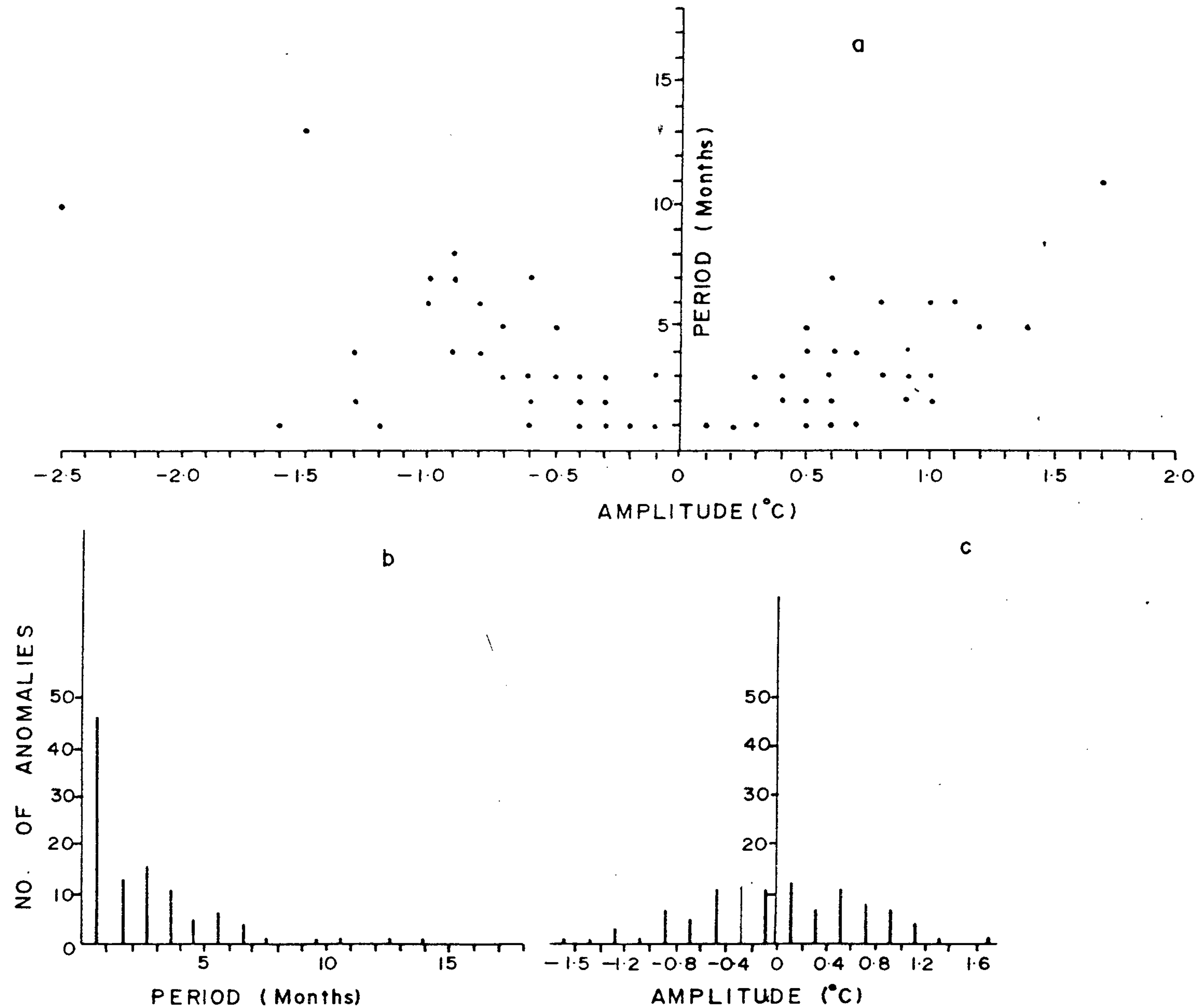


Fig. 31 SST anomalies in the Northern Arabian Sea
(Total 104)

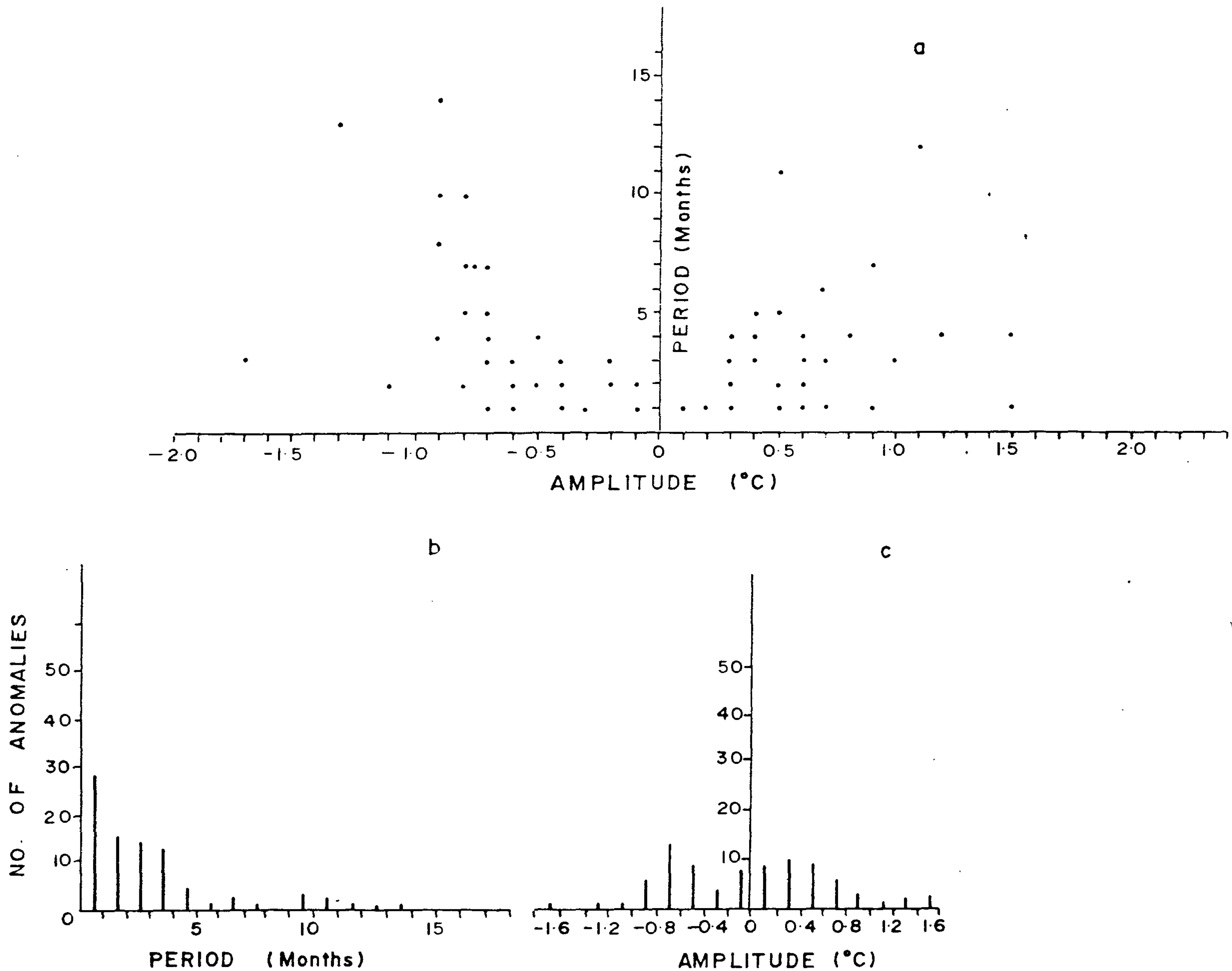


Fig.32 SST anomalies in the western Arabian Sea
(Total 93)

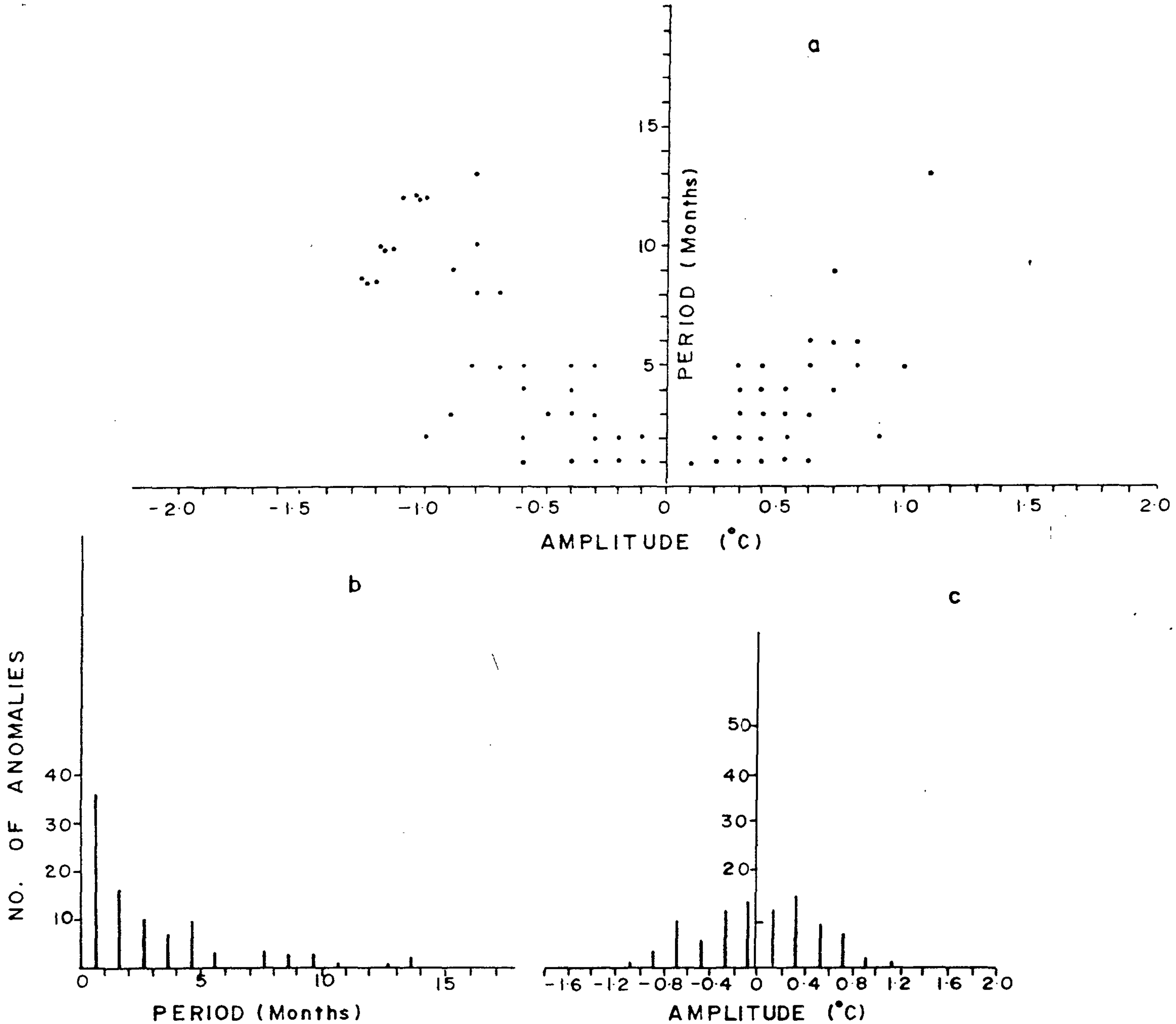


Fig.33 SST anomalies in the Central Arabian Sea .
(Total 90).

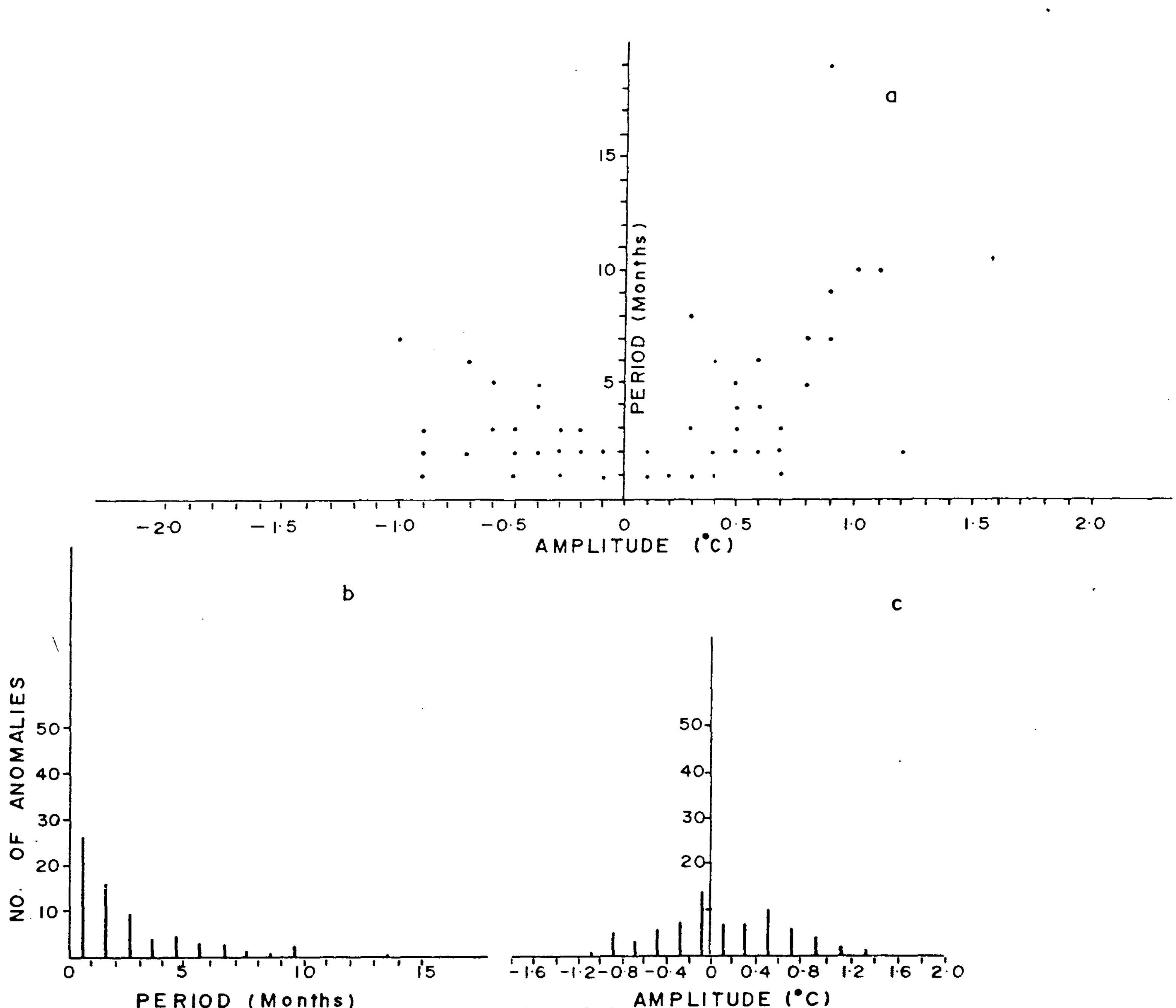


Fig. 34 SST anomalies in the Eastern Arabian Sea
(Total 70)

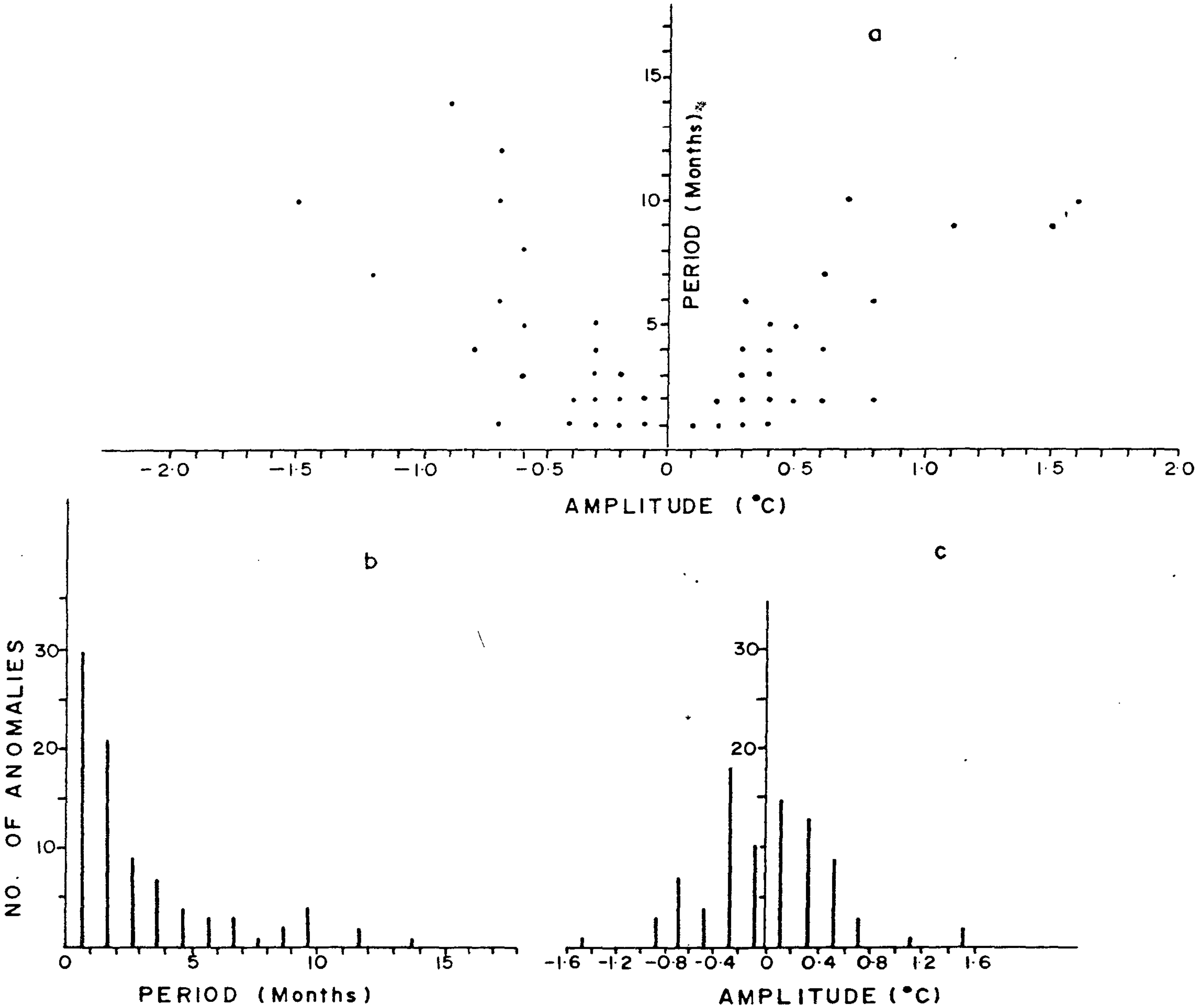


Fig. 35 SST anomalies in the Southern Arabian Sea
(Total 86)

CHAPTER VI

CHAPTER - VI

RELATIONSHIP BETWEEN SEA SURFACE TEMPERATURE, EVAPORATION, SOUTHERN OSCILLATION INDEX, MID TROPOSPHERIC CIRCULATION AND THE INDIAN MONSOON RAINFALL

In the present study we have tried to relate the mean seasonal SST of the four oceanic regions namely western AS (represented by MSQ 67), eastern AS (represented by MSQ 65), Bay of Bengal (MSQ 64) and off the Somalia coast region (MSQ 31) with the monsoon rainfall, the position of the 500 mb ridge in April along 75°E and the Southern Oscillation Index (SOI). The reason for choosing the above squares have been mainly the data density and its uniform distribution within the study period (1948-1972). The four Indian seasons being (i) Winter (January and February) (ii) Pre Monsoon (March, April, May) (iii) Monsoon (June, July, August, September) (iv) Post Monsoon (October, November, Decemeber).

The position of the 500 mb ridge in April along 75°E was found to be a very useful predictor for forecasting monsoon rainfall over the Indian subcontinent (Banerjee, 1978; Thapliyal, 1982; Mooley et al., 1986; Shukla and Mooley, 1987). We wanted to examine whether any causal relationship exists between the seasonal SST's over the various oceanic areas and the mid tropospheric circulation. Another parameter we thought which has a profound influence

on the monsoon rainfall was the SOI. Studies of Walker and Bliss (1932), Parthasarthy and Pant (1985), Elliott and Angell (1987) have shown that the Southern Oscillation (SO) plays a major role in modifying the mosoonal circulation and thus the monsoon rainfall.

From an analysis of the correlation between the seasonal SST's of the western AS, Monsoon rainfall, 500 mb ridge position and the SOI for the period 1948 to 1972 (Table 18) we found that the preceding winter SST (WSST) does not have any relationship with the monsoon rainfall but it is weakly and positively (at 80% level) correlated with the 500 mb ridge position. The WSST were negatively and significantly (at 95% level) correlated with the SOI. Suppiah (1988) has also obtained a similar result between Indian Ocean SST anomalies and SOI, he found strong negative correlations in the winter half of the year but weak negative correalations in the summer half. The latter, he feels may be due to the influence of summer monsoon. The premonsoon SST (PMSST) of this area are positively and significantly (at 95% level) correlated with the monsoon rainfall. Wu (1984) has also obtained weak positive correlatios between PMSST over a large oceanic area (equator - 15^{o}N; 50-75^{o}E) of the AS and the summer monsoon rainfall. Rao and Goswami (1988) feels that the reason for weak correlations may be the inclusion of the month of May. They feel that this month should be excluded from the premonsoon season as they think that the 30-50 day mode starts influencing the AS from May. The PMSST were weakly and positively (at 80% level) correlated with the position of the 500 mb ridge. The summer monsoon SST (MSST) were weakly and negatively (at 80% level) correlated with the monsoon rainfall and the position of the 500 mb ridge. The post monsoon SST (POMSST) of this oceanic region were found to be negatively and significantly correlated with the monsoon rainfall (at 95% level), and 500 mb ridge (at 98% level) and it is positively and significantly correlated with SOI (at 90% level).

Table 19 gives the correlation coefficients for the eastern AS. The PMSST of this area was positively and significantly correlated with the monsoon rainfall and 500 mb ridge (at 95% level). Joseph and Pillai (1986) have obtained a similar result. It was negatively and significantly correlated with the SOI(at 90% level). The MSST were negatively and significantly correlated with the rainfall and the position of the 500 mb ridge in April (at 95% level). The POMSST were negatively and significantly correlated with the monsoon rainfall (at 98% level) and 500 mb ridge (at 90% level) respectively. They were positively and significantly correlated (at 95% level) with the SOI.

The correlation coefficients between the seasonal

SST of Bay of Bengal, monsoon rainfall, 500 mb ridge position and SOI are presented in Table 20. The WSST were positively and significantly correlated with the monsoon rainfall (at 98% level), the position of the 500 mb ridge in April (at 95% level). They were weakly and negatively correlated with the SOI (at 80% level). The MSST were negatively and significantly correlated with the monsoon rainfall (at 95% level). The POMSST were negatively and significantly correlated with the monsoon rainfall (at 99% level) and 500 mb ridge position (at 95% level).

Table 21 gives the correlation coefficients of the relationships between the seasonal SST's off Somalia Coast and other parameters. The preceding WSST were weakly and negatively (at 80% level) correlated with the SOI. The PMSST were positively and significantly correlated with the monsoon rainfall (at 95% level), and 500 mb ridge(at 90% level). The MSST were negatively and significantly correlated with the 500 mb ridge position at 95% level). They were weakly and positively correlated with the SOI(at 80% level). The POMSST were negatively and significantly correlated (at 95% level) with the position of the 500 mb ridge.

We do not have any physical explanation as to why the PMSST in the AS and Somalia areas are positively and significantly related to the monsoon rainfall. The reason

for negative and significant correlation between MSST and monsoon rainfall may be due to the lowering of SST in the monsoon months over the AS, which in turn could strengthen the high pressure over the oceanic area and this in turn could consequently develop a strong pressure gradient between the AS and the Indian subcontinent which would result in an enhanced monsoon circulation and good monsoon rainfall.

There exists a strong teleconnection between the Indian summer monsoon rainfall, the Walker circulation and the southern oscillation as indicated by several studies. The SO is characterized by switching of the pressure systems between the eastern and western equatorial Pacific ocean and also an eastward shift of Walker circulation. This pressure change is associated with a shift in the warm pool from the western part of the equatorial Pacific to the east. This warm pool, according to Bjerknes (1969) is a region of large scale upward transport of moisture and is the main branch of Walker circulation. An examination of the global SST distribuion shows that an arm of this warm water pool extends to the Indian ocean through Bay of Bengal (Gopinathan and Rao, 1985). We feel that similar type of Walker type circulation during winter may be responsible for the positive and significant correlation between WSST of Bay of Bengal and monsoon rainfall over India.

Table 22 presents the mean seasonal (southwest monsoon) evaporation rates over the Arabian Sea (Area A), southern hemisphere (Area B) and the Bay of Bengal (Area C), for the period 1948 to 1972. From the table it is obvious that evaporation rates over the southern hemisphere is more than the AS and Bay of Bengal in general. The evaporation rates varied from 2.24 X 10^{10} tons/day in 1948 (minimum) to 3.69 X 10^{10} tons/day, in 1971 (maximum) for the AS.

The evaporation rates varied from 3.08 X 10^{10} tons/day in 1958 (lowest) to 5.76 X 10^{10} tons/day in 1970 (highest) over the southern hemisphere. In the case of Bay of Bengal the minimum values were observed in 1950 (1.44 X 10^{10} tons/day) and the maximum in 1970 (2.71 X 10^{10}) for the study period. In addition it was also found that the evaporation rates were higher over the southern hemisphere and Bay of Bengal during good monsoon years as compared to bad monsoon years.

Thus the present study on the relationships between the seasonal SST of various oceanic regions, monsoon rainfall, position of the 500 mb ridge along 75° E in April, evaporation rates over the AS, southern hemisphere and Bay of Bengal and SOI have brought out the following results:

(1) The PMSST of the three oceanic areas, namely the western AS, eastern AS and off Somalia coast regions

are positively and significantly correlated with the monsoon rainfall and hence can be thought of as useful predictors for the summer monsoon rainfall.

(2) The SST anomalies in the AS and Indian Ocean are result of the monsoon circulation/activity rather than vice versa, because the POMSST of all the above study areas were found to be neagtively and significantly correlated with the monsoon rainfall and the position of the 500 mb ridge position along 75^{o}E in April.

(3) The preceding WSST of the Bay of Bengal were found to be positively and significantly correlated with the position of the 500 mb ridge in April along 75^{o}E.

(4) The SOI was found to be weakly and negatively correlated with the WSST over Bay of Bengal and off Somalia coasts (at 80%) but significantly over the western AS (at 95%). The PMSST of over the eastern AS was found to be negatively and significantly correlated with the SOI (at 90%).

(5) The reason for not having good relationship between the evaporation rates over the Area A, B and C with the monsoon rainfall over the Indian subcontinent

may be that, not all the moisture coming from the Arabian Sea or southern hemisphere is utilized for the monsoon rainfall, a reasonable amount of this moisture would be used for precipitation over the southeast Asian countries. Hence only a detailed examination of the moisture flux coming and leaving the Indian subcontinent can throw better light on this aspect.

TABLE 18

Correlation between seasonal SST's in the western AS (MSQ 67), monsoon rainfall, 500 mb ridge and SOI

Parameters / Season	Monsoon rainfall	500 mb ridge	SOI
Winter	0.01	0.29^{1}	-0.41^{3}
Pre monsoon	0.41^{3}	0.30^{1}	-0.20
Monsoon	-0.30^{1}	-0.29^{1}	0.12
Post monsoon	-0.38^{3}	-0.45^{4}	0.35^{2}

Where the superscripts, 1,2,3,4 and 5 stand for 80%, 90%, 95%, 98% and 99% confidence levels respectively.

TABLE 19

Correlation between seasonal SST's in the eastern AS (MSQ 65), monsoon rainfall, 500 mb ridge and SOI

Parameters / Season	Monsoon rainfall	500 mb ridge	SOI
Winter	0.09	0.14	-0.16
Pre monsoon	0.40^{3}	0.39^{3}	-0.35^{2}
Monsoon	-0.40^{3}	-0.39^{3}	0.00
Post monsoon	-0.49^{4}	-0.34^{2}	0.44^{3}

Where the superscripts, 1,2,3,4 and 5 stand for 80%, 90%, 95%, 98% and 99% confidence levels respectively.

TABLE 20

Correlation between seasonal SST's in the Bay of Bengal (MSQ 64), monsoon rainfall, 500 mb ridge and SOI

Parameters Season	Monsoon rainfall	500 mb ridge	SOI
Winter	0.47^{4}	0.36^{3}	-0.29^{1}
Pre monsoon	0.13	-0.02	-0.15
Monsoon	-0.43^{3}	-0.03	0.19
Post monsoon	-0.53^{5}	-0.38^{3}	-0.07

Where the superscripts, 1,2,3,4 and 5 stand for 80%, 90%, 95%, 98% and 99% confidence levels respectively.

+TABLE 21

Correlation between seasonal SST's off the Somalia coast (MSQ 31), monsoon rainfall, 500 mb ridge and SOI

Parameters Season	Monsoon rainfall	500 mb ridge	SOI
Winter	0.17	0.06	-0.27^{1}
Pre monsoon	0.41^{3}	0.36^{2}	-0.11
Monsoon	-0.15	-0.43^{3}	0.29^{1}
Post monsoon	-0.21	-0.39^{3}	0.11

Where the superscripts, 1,2,3,4 and 5 stand for 80%, 90%, 95%, 98% and 99% confidence levels respectively.

TABLE 22

Seasonal mean evaporation rates over AS (Area A), SH(Area B) and Bay of Bengal (Area C) for the period 1948 to 1972.

Units : 10^{10} tons.day

Year/Area	Area A	Area B	Area C
1948	2.37	3.79	1.68
1949	2.24	3.32	1.63
1950	2.30	3.33	1.44
1951	2.28	3.93	1.57
1952	2.34	3.78	1.56
1953	2.48	3.61	1.65
1954	2.43	3.83	1.71
1955	2.36	3.54	1.67
1956	2.35	4.26	2.12
1957	2.54	3.62	1.80
1958	2.39	3.08	1.80
1959	2.74	3.52	1.64
1960	2.75	3.42	2.22
1961	2.87	5.62	2.33
1962	2.78	3.68	2.37
1963	2.71	4.55	1.92
1964	2.48	4.55	1.64
1965	2.48	4.26	1.88

Year/Area	Area A	Area B	Area C
1966	2.44	4.35	1.72
1967	2.35	4.72	1.67
1968	2.62	5.06	1.64
1969	2.48	4.22	1.67
1970	2.90	5.76	2.71
1971	3.69	5.46	2.08
1972	3.07	4.93	2.00

CHAPTER VII

CONCLUSIONS

A summary of the original contributions and findings of the present study on the surface heat budget of the Indian Ocean are given below:

(a) The annual mean net flux divergence values over the tropical Indian Ocean show that the evaporation exceeds precipitation over most of the study area except the Bay of Bengal region, where there exists large scale convergence.

(b) The evaporation rates on a seasonal scale were found to be same over the Arabian Sea irrespective of the monsoon activity over the Indian subcontinent.

(c) The southern hemispheric moisture was found to play a major role in the Indian monsoon activity during all the months (June to September), with the moisture almost double the AS values in the month of August, when the maximum break in monsoon conditions are observed over the subcontinent.

(d) Large negative anomalies of SST off the Somalia and Arabian coasts were found indicating the effect of strong monsoonal cooling during the active periods of July , August and September of good monsoon seasons.

(e) An analysis of the sea surface temperature anomalies in the AS has shown that the short duration anomalies (i.e., anomalies with periods less than 4 months) are driven by the surface heat fluxes. The medium duration anomalies (i.e., anomalies with periods between 5 and 10 months) are driven by advection (both horizontal and vertical) and other oceanic processes.

(f) A further analysis has shown that the SST anomalies are well correlated with the air temperature anomalies and latent heat flux anomalies and least correlated with the wind stress anomalies and net radiation anomalies.

(g) The preceding mean winter SST's of the Bay of Bengal area was found to be positively and significantly correlated with the midtropospheric circulation in April.

(h) We also feel that the SST anomalies in the AS and in the Indian Ocean are caused by the atmospheric circulation anomalies / monsoon activities rather than vice versa, which is shown by the negative and significant correlations between the midtrospheric circulation , monsoon rainfall with the monsoon and post monsoon SST's over the various study areas.

(i) The study shows that there is a weak linkage between the SOI and the seasonal SST's over most of the study areas except on few occassions, when it is significantly correlated.

(j) The estimate of mean annual meridional heat transport of the tropical Indian Ocean computed for the period 1948-1972 was found to be southward at all latitude belts with the exception of higher latitudes in the southern hemisphere. This result agrees with the previous studies in direction but differs in magnitude.

(k) Large scale international programmes on the lines similar to MONEX-73, MONSOON-77 and MONEX-79, for obtaining accurate estimates of the transfer coefficients for the study area, can give better insight about the role of the various surface fluxes and their input towards the monsoon circulation.

(l) Simultaneous upper air observations along the equator, off the west coast of India and the east coast are needed for monitoring how much of the cross equatorial moisture from the southern hemisphere is utilized for the Indian summer monsoon rainfall.

(m) Simultaneous upper air observations along the equator, off the west coast of India and the east coast are needed for monitoring how much of the cross equatorial moisture from the southern hemisphere is utilized for the Indian summer monsoon rainfall.

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ANNEXURE A

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      PROGRAM SSTAN

C     PROGRAM COMPUTES AND LISTS SST ANOMALIES WHOSE
C     PERIOD LIE BETWEEN CPERMN AND CPERMX AND ALSO
C     CHECKS FOR THE VARIOUS CAUSATIVE FACTORS

      DIMENSION IYEAR(300), IMONTH(300)
      DIMENSION SST(300), SSTMMT(12), SSTMM(12), SSTAN(300)
      DIMENSION TAU(300), TAUMMT(12), TAUMM(12), TAUAN(300)
      DIMENSION HGO(300), HGOMMT(12), HGOMM(12), HGOAN(300)
      DIMENSION ERS(300), ERSMMT(12), ERSMM(12), ERSAN(300)
      DIMENSION ZERO(300), ANPS(300), ANPE(300), ANPER(300)
     1          ANAMP(300)

      INTEGAR YEAR,WIND,EAST,WDIR,PRES,PPTOT
      REAL  ICER,IRED,LATB,LATI,NNPERC,NCPERC
      CHARACTER *2 SIGNAL,NEGATI,POSITI,NOTCLE
      INTEGAR *4 FLOAT
      CHARACTER FILNAM*20
      DATA NEGATI/'NN'/
      DATA POSITI/'PP'/
      DATA NOTCLE/'NC'/

      WRITE(6,2000)
2000  FORMAT('$', 'NAME OF FILE CONTAINING DATA')
      READ(6,'(A20)')FILNAM
      OPEN(11,FILE=FILNAM,ACCESS='SEQUENTIAL',STATUS='OLD')
      WRITE(6,2500)
2500  FORMAT('$','OUTPUT FILE NAME')
      READ(6,'(A20)')FILNAM
      OPEN(12,FILE=FILNAM,ACCESS='SEQUENTIAL',STATUS='NEW')
      READ(11,801)MRSQ,ISTYR,ISTMN,ILYR,ILMN,IRECLE,MLAT,
     1 MLON,CLAT,CLON
 801  FORMAT('SST ANALYSIS USING BUNKER DATA',//,
     1       'MARSDEN SQUARE                            : ',I4,/,
     2       'YEAR OF FIRST DATA RECORD                 : ',I5,/,
     3       'MONTH OF FIRST DATA RECORD                : ',I4,/,
     4       'YEAR OF LAST DATA RECORD                  : ',I5,/,
     5       'MONTH OF LAST DATA RECORD                 : ',I4,/,
     6       'MIDDLE LAT OF MARSDEN SQUARE              : ',I6,/,
     7       'MIDDLE LONG OF MARDEN SQUARE              : ',I6,/,
     8       'WEIGHTED CENTER OF OBSERVATIONS (LAT)     : ',F7.2,/,
     9       'WEIGHTED CENTRE OF OBSERVATIONS (LONG)    : ',F7.2,/)

      NTOTMN=12*(ILYR-(ISTYR-1)+ILMN+(12-(ISTMN-1))
      WRITE(12,821) NTOTMN
 821  FORMAT('TOTAL NUMBER OF MONTHS COVERED ', I7,/)
      DO 100 I=1,NTOTMN
      READ(11,831)MSQU,YEAR,MON,NOBS,TSEA,HGB,QSUR,TAUX,TAUY)
 831  FORMAT(I4,I5,I4,I6,F5.1,F6.1,F6.1,F5.1,F5.1)
      IYEAR(I)=YEAR
      IMONTH(I)=MON
      SST(I)=TSEA
      TAUX=10.0*TAUX
      TAUY=10.0*TAUY
      TAU(I)=SQRT(TAUX**2.0+TAUY**2.0)
      HGO(I)=HGB(I)
```

```
      ERS(I)=QSUR
      TMON(I)=FLOAT(I)-0.5
      IF(NOBS.EQ.0) WRITE(12,832)YEAR,MON
832   FORMAT('ZERO OBSERVATIONS IN YEAR', I4,',MONTH', I2)
100   CONTINUE

      DO 110 I=1,12
      SSTMMT(I)=0.0
      TAUMMT(I)=0.0
      HGOMMT(I)=0.0
      ERSMMT(I)=0.0
110   CONTINUE

      DO 120 I=1,NTOTMN
      SSTMMT(IMONTH(I))=SSTMMT(IMONTH(I))+SST(I)
      TAUMMT(IMONTH(I))=TAUMMT(IMONTH(I))+TAU(I)
      HGOMMT(IMONTH(I))=TAUMMT(IMONTH(I))+HGO(I)
      ERSMMT(IMONTH(I))=ERSMMT(IMONTH(I))+ERS(I)
120   CONTINUE
      DO 130 I=1,12
      SSTMM(I)=SSTMMT(I)/25.0
      TAUMM(I)=TAUMMT(I)/25.0
      HGOMM(I)=HGOMMT(I)/25.0
      ERSMM(I)=ERSMMT(I)/25.0
130   CONTINUE

      DO 140 I=1,NTOTMN
      SSTAN(I)=SST(I)-SSTMM(IMONTH(I))
      TAUAN(I)=TAU(I)-TAUMM(IMONTH(I))
      HGOAN(I)=HGO(I)-HGOMM(IMONTH(I))
      ERSAN(I)=ERS(I)-ERSMM(IMONTH(I))
140   CONTINUE

      JZER=1
      DO 170 I=1,(NTOTMN-1)
      IF(SSTAN(I)*SSTAN(I+1).LT.0.0) THEN
              ZERO(JZER)=(TMON(I+1)+TMON(I))/2.0
                      JZER=JZER+1
      ELSE
              CONTINUE
      ENDIF
170   CONTINUE
      MAXZER=JZER
      MAXAN=MAXZER-2

      DO 180 I=1,MAXAN
      ANPS(I)=ZERO(I)
      ANPE(I)=ZERO(I+1)
      ANPER(I)=ANPE(I)-ANPS(I)
180   CONTINUE

      DO 200 I=1,MAXAN
      JINI=IFIX(ANPS(I)+1.0)
      JFIN=IFIX(ANPE(I)
      ANAMP(I)=0.0
      DO 190 J=JINI,JFIN
        IF (SSTAN(J).GE.0.0) THEN
           IF (SSTAN(J).GT.ANAMP(I))ANAMP(I)=SSTAN(J)
              ELSE
                 IF (SSTAN(J).LT.ANAMP(I))ANAMP(I)=SSTAN(J)
```

```
      ENDIF
190   CONTINUE
200   CONTINUE

      DO 210 I=1,MAXAN
      ANPS(I)=ZERO(I)
      ANPE(I)=ZER(I+1)
      ANPER(I)=ANPE(I)-ANPS(I)
210   CONTINUE

      ANMAXP=0.0
      ANMAXN=0.0
      NPOSAN=0
      NNEGAN=0
      PEMAXN=0.0
      PEMAXP=0.0

      DO 220 I=1,MAXAN
      IF (ANAMP(I).GE.0.0) THEN
      IF (ANAMP(I).GT.ANMAXP) ANMAXP=ANAMP(I)
      IF (ANAMP(I).GT.PEMAXP) PEMAXP=ANPER(I)
      ELSE
      IF (ANAMP(I).LT.ANMAXN) ANMAXN=ANAMP(I)
      IF (ANPER(I).GT.PEMAXN) PEMAXN=ANPER(I)
      ENDIF
 220  CONTINUE

      WRITE(*,901)
 901  FORMAT('MINIMUM PERIOD=? (IN F FORMAT)',/)
      READ(*,902)CPERMN
 902  FORMAT(F10.2)
      WRITE(*,903)
 903  FORMAT('MAXIMUM PERIOD=? (IN F FORMAT)',/)
      READ(*,904)CPERMX
 904  FORMAT(F10.2)

      NCRTOT=0
      WRITE(12,916)CPERMN,CPERMX
      FORMAT('CHARACTERSTICS OF ANOMALIES WITH PERIODS',/,
     1        'GREATER THAN OR EQUAL TO 'F7.2,' MONTHS',/,
     2        'AND LESS THAN OR EQUAL TO 'F7.2,'MONTHS',/)

      NNTOT=0
      PPTOT=0
      NCTOT=0
      DO 270 J=(IFIX(ANPS(I)+1),(IFIX(ANPE(I))
      WRITE(12,921)I,ANPS(I),ANPE(I)
 921  FORMAT(/,'ANOMALY NUMBER=',I4,/,
     1         'START TIME (MONTH SCALE)=',F7.2,/,
     2         'END TIME (MONTH SCALE)=',F7.2)
      SSTAV=0.0
      TAUAV=0.0
      HGOAV=0.0
      ERSAV=0.0
      DO 270 J=(IFIX(ANPS(I))+1),(IFIX(ANPE(I))
      WRITE(12,266)IYEAR(J),IMONTH(J),SSTAN(J),TAUAN(J)
     1            HGOAN(J),ERSAN(J)
 266  FORMAT(2I7,4F10.2)
      SSTAV=SSTAV+SSTAV(J)
      TAUAV=TAUAV+TAUAV(J)
```

```
      HGOAV=HGOAV+HGOAV(J)
      ERSAV=ERSAV+ERSAV(J)
270   CONTINUE

      SSTAV=SSTAV/ANPER(I)
      TAUAV=TAUAV/ANPER(I)
      HGOAV=HGOAV/ANPER(I)
      ERSAV=ERSAV/ANPER(I)
      IF (((SSTAV.LT.0.0).AND.(TAUAV.GT.0.0))
     1                   .AND.(HGOAV.LT.0.0)) SIGNAL=POSITI
      IF(((SSTAV.LT.0.0).AND.(TAUAV.GT.0.0))
     1                   .AND.(HGOAV.GT.0.0)) SIGNAL=NOTCLE
      IF(((SSTAV.LT.0.0).AND.(TAUAV.LT.0.0)
     1                   .AND.(HGOAV.LT.0.0)) SIGNAL=NOTCLE
      IF(((SSTAV.LT.0.0).AND.(TAUAV.LT.0.0)
     1                   .AND.(HGOAV.LT.0.0)) SIGNAL=NEGATI
      IF(((SSTAV.GT.0.0).AND.(TAUAV.GT.0.0))
     1                   .AND.(HGOAV.LT.0.0)) SIGNAL=NEGATI
      IF(((SSTAV.GT.0.0).AND.(TAUAV.GT.0.0))
     1                   .AND.(HGOAV.GT.0.0)) SIGNAL=NOTCLE
      IF(((SSTAV.GT.0.0).AND.(TAUAV.LT.0.0))
     1                   .AND.(HGOAV.LT.0.0)) SIGNAL=NOTCLE
      IF(((SSTAV.GT.0.0).AND.(TAUAV.LT.0.0))
     1                   .AND.(HGOAV.GT.0.0)) SIGNAL=POSITI

      WRITE(12,926)SSTAV,TAUAV,ERSAV,SIGNAL
926   FORMAT(14X,4('---------'),/,14X,4F10.2,15X,A2)

      IF(SIGNAL.EQ.POSITI) PPTOT=PPTOT+1
      IF(SIGNAL.EQ.NEGATI) NNTOT=NNTOT+1
      IF(SIGNAL.EQ.NOTCLE) NCTOT=NCTOT+1
275   CONTINUE
280   CONTINUE

      PPPERC=(FLOAT(PPTOT)/FLOAT(NCPTOT))*100.0
      NNPERC=(FLOAT(NNTOT)/FLOAT(NCPTOT))*100.0
      NCPERC=(FLOAT(NCTOT)/FLOAT(NCPTOT))*100.0
      WRITE(12,930)NCPTOT,PPTOT,PPPERC,NNTOT,NNPERC
     1              NCTOT,NCPERC
930   FORMAT(//,
     1 'TOTAL NUMBER OF ANOMALIES SATISFYING CONDITION ON PERIOD=',I5,/
     2 'NUMBER OF ANOMALIES CONSISTENT WITH FLUXES DRIVING SST=',I5,
     2 '('F5.1,'PERCENT)',/,
     3 'NUMBER OF ANOMALIES INCONSISTENT WITH FLUXES DRIVING SST=',I5,
     3 '(',F5.1,'PERCENT)',/,
     4 'NUMBER OF ANOMALIES WHERE THINGS ARE NOT CLEAR=',I5,/,
     4 '('F5.1,'PERCENT)'

      CLOSE(11)
      CLOSE(12)
      STOP
      END
```

ABBREVIATIONS USED IN THE PROGRAM

MSQU	:	MARSDEN SQUARE NUMBER
YEAR	:	YEAR
MON	:	MONTH
NOBS	:	NUMBER OF OBSERVATIONS
TSEA	:	SEA SURFACE TEMPERATURE (DEGREES CELSIUS)
HGB	:	HEAT GAIN OVER THE OCEAN (WATTS/SQ.M)
TAUX	:	X COMPONENT OF WIND STRESS (DYNES/SQ.CM)
TAUY	:	Y COMPONENT OF WIND STRESS (DYNES/SQ.CM)
QSUR	:	EFFECTIVE RADIATION AT THE SEA SURFACE (WATTS/SQ.M)
SST	:	SEA SURFACE TEMPERATURE (DEGREES CELSIUS)
TAU	:	WIND STRESS (DYNES/SQ.CM)
HGO	:	HEAT GAIN OVER OCEAN (WATTS/SQ.M)
ERS	:	EFFECTIVE RADIATION AT THE SURFACE (WATTS/SQ.M)
CPERMN	:	MINIMUM PERIOD OF SST ANOMALY (MONTH)
CPERMX	:	MAXIMUM PERIOD OF SST ANOMALY (MONTH)
SSTMMT	:	SST MONTHLY MEAN TOTAL
TAUMMT	:	TAU MONTHLY MEAN TOTAL
HGOMMT	:	HGO MONTHLY MEAN TOTAL
ERSMMT	:	ERS MONTHLY MEAN TOTAL
SSTMM	:	SST MONTHLY MEAN
TAUMM	:	TAU MONTHLY MEAN
HGOMM	:	HGO MONTHLY MEAN
ERSMM	:	ERS MONTHLY MEAN
SSTAN	:	SST ANOMALY
TAUAN	:	TAU ANOMALY
HGOAN	:	HGO ANOMALY
ERSAN	:	ERS ANOMALY
ANPS	:	ANOMALY START TIME (MONTH)
ANPE	:	ANOMALY END TIME (MONTH)
ANPER	:	ANOMALY PERIOD (MONTH)
ANAMP	:	ANOMALY AMPLITUDE (DEGRESS CELSIUS)
ANMAXP	:	MAXIMUM POSITIVE ANOMALY AMPLITUDE (DEGREES CELSIUS)
ANMAXN	:	MAXIMUM NEGATIVE ANOMALY AMPLITUDE (DEGREES CELSIUS)
NPOSAN	:	NUMBER OF POSITIVE ANOMALIES
NNEGAN	:	NUMBER OF NEGATIVE ANOMALIES
PEMAXP	:	PERIOD OF MAXIMUM POSITIVE ANOMALY (MONTH)
PEMAXN	:	PERIOD OF MAXIMUM NEGATIVE ANOMALY (MONTH)