1

CHAPTER I

1.1 INTRODUCTION

The importance of the summer monsoon in influencing the Indian economy can hardly be over emphasised. This monsoon which prevails over India during June to September exhibits substantial inter-annual variations which lead to either drought conditions or flood situations. The origin of it can best be described as follows.

During the Northern summer, the south east trades from Southern Hemisphere recurve while crossing the Equator and come into Southern Asia as south west monsoon with three main branches, one in the Arabian Sea, one in the Bay of Bengal and one in the South China Sea. Of these the air current over Arabian Sea is more intense and steady. Most parts of South Asia, particularly India, receives most of its annual rainfall during this monsoon period. Krishnamurthy et al (1981) consider onset vortex over Arabian Sea as a characteristic circulation feature heralding the onset of the Indian Summer Monsoon. Pearce and Mohanty (1984) concluded that the onset consists of a moisture building up stage and a subsequent intensification of winds over the Arabian Sea and increased latent heat release.
The different ways in which the ocean could influence the climate can be described as due to the physical and thermal properties of water. Because of the large volume, heat capacity and absorptivity of these water sources, they form an important source of heat and moisture to the atmosphere. The oceans have a large thermal inertia which cause a time lag between the absorption, redistribution and release of the solar energy and hence effectively influence the variations in climate.

The ocean and the atmosphere together act as a coupled system in a complex manner and controls one another. Various studies have indicated that tropical oceans have greater influence on the general circulation of the atmosphere than extra tropical oceans. Among the tropical oceans, the Indian Ocean sector is unique in its characteristics because of its spectacular seasonal changes. On account of its complexity, the studies of moisture and heat budget would become doubly important in the Arabian Sea. The monsoon experiments MONSOON-77 and MONEX-79 provided data and details necessary for a better understanding of the meteorology over the Indian Ocean. The Indian Summer Monsoon characterised by the seasonal reversal of wind is believed to be caused by the differential heating of land and sea which in turn is due to the asymmetric continentality and seasonal march of the sun, and hence the Arabian
Sea with its complex SST pattern might feedback the overlying atmosphere. Hastenrath (1985) describes that pressure over land and wind speed over Arabian Sea act inversely, before the onset of the monsoon. It was also inferred that the region of warmest water and surface pressure moves northward in the Indian Ocean from February to July.

The evaporation over the sea which is the principal moisture source of the atmosphere is influenced by the sea surface temperature. The dramatic cooling of the Arabian Sea by a few degrees from April to August every year poses some serious questions about the mutual role of the monsoon and the Arabian Sea surface temperature. It is logical to think that these changes of evaporation and the consequent sea surface temperature changes might be associated either directly or indirectly with the rainfall received over the country in general and along the westcoast of India in particular. It will not be out of context to state that probably Arabian Sea surface temperature may be one of the potential predictors of the rainfall over India, although most of the proposed indicators seem to be more controlled by the monsoon rather than controlling it. However this should not defer investigators from exploring the possible indicators that influence the behaviour of monsoon. The numerous ongoing studies towards this end are the best examples for a determined effort to arrive at least at stati-
tical indicators for predicting the monsoon. The results of these studies differ, mainly because of the difference in the data sets and approaches to the problem. Since this aspect is still open for further studies, an attempt is made to study the relation between Arabian Sea surface temperature and the rainfall along the West coast of India. West coast is chosen for the study because, the influence of Arabian Sea surface temperature should be more in this region since the monsoon enters the country through this coast.

The detailed objectives of the thesis are presented hereunder.

1. To study over the stationary ship polygon positions in Arabian Sea during 1977 and 1979, the diurnal and day to day variations of -

   (a) Specific humidity, precipitable water vapour, wind, vorticity, divergence, vertical velocity and kinetic energy.

   (b) Moisture budget including the evaporation and the moisture flux divergence.

   (c) Heat budget including sensible heat and heat flux divergence.
2. To study the relation between Arabian Sea surface temperature and the monsoon rainfall along the west coast of India for a six year period including the MONEX years.

1.2 REVIEW OF LITERATURE

This section constitutes the literature available on earlier studies in the field. However to give a very detailed literature survey on monsoons is not only a very difficult task but also beyond the scope of the present study. For the sake of completeness a brief survey of the recent studies only are presented which may not be exhaustive but adequate enough to present the knowledge in this field.

From the various studies in the recent years, the role of oceans in influencing the atmospheric processes have become quite evident. During the last few decades, there have been many attempts (Pisharoty, (1965, 1981), Bhumralkar (1978), Shukla (1975, 1976, 1986) to find some oceanic parameters as predictors for the Indian Summer Monsoon. Although the relative importance of these parameters is still in dispute, studies made by Bunker* (1965), Pisharoty (1965, 1981), Ramage (1966, 1971), Ananthakrishnan (1968), Das (1968, 1985, 1986), Rao and Desai (1971), Rao (1970), Bhumralkar (1978), Krishnamurthy (1978), Sharma et al

In general, any large water body acts as a significant source of water vapour to the atmosphere. However, only when the motion field develops low level convergence, this water vapour is transported aloft. For further moistening of the air column, convergence in the middle level is equally important. Circulation parameters such as wind, divergence, vorticity, kinetic energy, vertical velocity, and amount of water vapour in the atmosphere above the area have therefore been studied. Ramage (1966), Findlater (1969(a) and 1969(b), Ali (1980), Bhide et al (1982) and Mooley and Parthasarathy (1983) have studied the different circulation parameters influencing the Indian monsoon. Das (1962), studied the east-west Walker cells in the Indian longitudes. Shukla and Sajnani (1971) pointed out that with all the limitations in the wind data accuracy and grid length used for finite difference technique, the computed divergence depicts reasonable values which are also synoptically consistent and exhibit systematic changes from day to day and from one level to another.

Wyrtki (1971) produced an Oceanographic atlas using the IIOE data, which serves as a valuable reference to the
values of different meteorological parameters over the Arabian Sea area. Bhumralkar (1974) reported that air-sea exchanges over the sea do not control the fluctuations of the monsoon but are themselves influenced by the variations of the monsoon flow. Appa Rao and Murthy (1977) evaluated the values of the precipitable water, mean and eddy transport of moisture and the vergence patterns over the Indian sub-continent, during two contrasting summer monsoons. They noted that in a good monsoon year there were (a) increased zonal and meridional transports, (b) stronger divergence and convergence patterns and (c) marginally higher precipitable water compared to a bad monsoon year.

Using MONEX-'79 dropsonde data, over the Arabian Sea and Indian West coast region, Ali (1980) analysed charts for a 48 hour period and found that a low level strong wind current with high shearing values is present in the southwest monsoon current. The speed of this current decreases steadily with height and finally around 500 mb level, the zonal direction was reversed from westerly to easterly. Rao and Webdell (1981) estimated the divergence, vorticity and humidity of air columns at various locations in the Arabian Sea. They pointed out that the areas of weak vertical velocities were characterised by low level convergence while that of divergence by gentle subsidence. Sinha and Sharma (1981) have presented a review on the different methods of
solving the omega equation to calculate the vertical velocity. Studies by Cadet and Reverdin (1981) and Cadet (1983), showed that the establishment of the strong circulation associated with the onset of monsoon is followed with a lag of 2 to 3 days, by a temperature drop of 2°C. There is also a significant positive correlation between the intensity of the wind over the Arabian Sea and monsoon activity over Central India. Ramanathan (1981, 1982) have studied the onset of monsoon and the atmospheric boundary layer over the Arabian Sea using MONEX '79 data. He found that the day to day variations of the parameters showed two periods of convective activity - one at the beginning of the onset period and the other during the active monsoon period, both being in June.

Bhide et al (1982) observed that during the onset phase of 1979 summer monsoon, organised convective synoptic scale systems such as (a) an easterly wave, (b) a cyclonic Vortex (on 8-9 June) and (c) a cyclonic circulation produced disturbed weather situation during June 1977. Chuchkalov (1982) have discussed the vertical structure of the Arabian Sea in different synoptic situations, taking into consideration the complex layer structure of the tropical and equatorial atmosphere. Howland and Sikdar (1983) studied the wind fields over the Arabian Sea for 1979 using a variety of data sources. They employed the kinematic method
to calculate divergence and O'Brien's technique to adjust the divergence of a column of atmosphere to calculate vertical velocity. They found that, the kinematic profiles of wind, divergence and vertical velocity undergo almost a complete reversal during the monsoon season.

There had been many attempts to relate the monsoon rainfall with the tropical circulation features. Mooley and Parthasarathy (1983) have found a wet and dry index for the Indian monsoon rainfall and correlated them with the tropical circulation features such as Southern Oscillation and El-Nino.

Bavadekar (1984) has explained the methods to compute the water vapour flux along a boundary wall and also has tabulated the moisture budget values for different years.

Ray and Bedi (1985) investigated the thermodynamic and kinematic structure of the troposphere over the Arabian Sea and Bay of Bengal during the Southwest monsoon season, making use of the ship polygon data taken during MONEX '79. They found that during the pre-onset phase, the flow was rather weak with dominantly subsiding motion and low moisture content while the onset phase was characterised by an increase in the kinetic energy as well as moisture content over the Arabian Sea. The height of the level of non-
divergence over Arabian Sea during pre-onset period was around 700 mb. The above mentioned studies gave a suitable background knowledge on the circulation and synoptic features over the Arabian Sea during the southwest monsoon months.

Moisture budget studies generally involve the computation of evaporation and latent heat flux together with moisture divergence or convergence by wind. Pisharoty (1965) was among the first to compute the water vapour budget of the lower troposphere over the Arabian Sea. He considered a cuboidal volume with its bottom at the sea level, and top at 450 mb level, eastern boundary along 42°E, western boundary along 75°E, northern boundary along 26°N and southern boundary along the equator. He computed net fluxes of water vapour across the equator into the sea and from the Arabian Sea across the West coast of India. His estimates suggested that more than half of the moisture crossing the West coast of India, was supplied by evaporation from the Arabian Sea and the remainder originating in the Southern Hemisphere and crossing the equator, between 42° and 75°E.

Saha (1970), using additional data recomputed the moisture fluxes across the equatorial box of rectangular volume over the above mentioned area and contrary to
Pisharoty's results found that the flux of water vapour across the equator is about 30% larger than the evaporation over the Arabian Sea. Saha and Suryanarayana (1972) computed the mean monthly values of vertical fluxes of sensible and latent heat from the surface of Indian Ocean for a five year period and showed that in 1967, the area under negative sensible heat flux extended southward to almost equator and to 70°E longitude. They found that the pattern is comparable to that during 1964 in areas extent as well as magnitude and both were good monsoon years. Their investigation on evaporation flux over Arabian sea showed that the region of low flux values coincided with the regions of upwelling and cold sea surface. Saha and Bavadekar (1973) later on studied the budget of water vapour of the lower troposphere (below 450 mb) by computing both mean and eddy motions. They used the following equation to compute fluxes

\[ F = \frac{1}{g} \int_{p_t}^{p_b} \int_{l} \nabla(p,l) q(p,l) dl dp \]

(The symbols have their usual meanings). The horizontal as well as vertical walls were divided into many segments and then integrated. Relative magnitudes of net cross-equatorial flux of water vapour into the volume and evaporation from the surface of the Arabian Sea appear to suggest that on an average the former may be about 30 percent larger than the latter.
Bhumralkar (1978) has shown that there was considerable increase in moisture content downstream of the monsoon air mass over the Eastern Arabian Sea before it strikes the West coast of India. Hastenrath and Lamb (1980) also found that a large portion of the moisture evaporating from Southern Tropical Indian Ocean during the northern summer is being carried northward across the equator in the lower layers of the monsoon flow.

Studies by Peixoto and Oort (1983) indicated the importance of the Tropical South Indian Ocean and the subordinate role of the Arabian Sea as a water vapour source for the Indian summer monsoon.

Cadet (1981) and Cadet and Reverdin (1981) examined the water vapour transport over the Indian Ocean and reported that 70% of the water vapour crossing the West coast of India come from the Southern Hemisphere and the remaining could be from the Arabian Sea evaporation. More than 50% of the total cross equatorial moisture flow was through the region between 45° and 60°E. Thus, it can be seen that, there are differences of opinion about the source region of moisture for the monsoon flow.

It may be mentioned that most of the above studies had been based on sparse upper air observations and availability of ISMEX-73 data helped many more to work on this
aspect. Jambunathan and Ramamurthy (1975) noticed no significant difference in temperature and moisture contents, between active and weak monsoons in the very lower atmosphere during 1973. Using same data, Pant (1977) calculated the heat and moisture fluxes over the Arabian sea area and concluded that during disturbed weather conditions, sensible heat flux shows a decrease. He also found a well defined diurnal variation for the sensible heat with a maximum positive flux around midnight and minimum around mid-day. In a similar study but using climatological data, Rao et al (1977) reported that during monsoon break there is a net loss of heat over Northern Arabian Sea and a net heat gain over the Bay of Bengal.

Saha and Bavadekar (1977) extended their earlier study (1973) using a nine year (1964-72) data set and got good correlations (0.87) between net moisture flux across the West coast of India south of Bombay and the monsoon rainfall. A later study by Bavadekar and Khaladkar (1982) for contrasting monsoon seasons revealed that zonal transport of moisture during good monsoon period is more in the West coast sector, south of Bombay.

Ghosh et al (1978) also using ISMEX-73 data calculated the water vapour budget over the Arabian Sea and drew conclusions supporting Pisharoty (1965). They further
reported that evaporation exceeded precipitation in the East Arabian Sea near the West coast of India and also found that there are no significant changes in the fluxes across the Equator at 50°E between active and weak monsoon periods.

Rao et al (1981) found that greater evaporation occurred over the Arabian Sea area before the onset of monsoon and after complete onset, there is a decrease in evaporation by 30 to 40 percent.

Ramanadham et al (1981) using MONSOON-77 data found that the latent heat flux associated with the onset vortex over Arabian sea is larger than that associated with a depression over north Bay of Bengal.

Rao et al (1981) compared estimated evaporation values over the Arabian Sea with rainfall derived from satellites for the three summer seasons of 1973, 1974 and 1977. They found that the total precipitation over Arabian Sea was only 40% of the evaporation during these seasons and they hypothesised that the remaining part might have been transported into the Indian sub-continent.

In yet another study, Bavadekar (1982) has calculated the monthly mean transfer of water vapour in the layer below 700 mb for India, for the years 1962-1972, and correlated them with summer monsoon rainfall. The correlations were negative or small positive values for different periods.
Murakami et al (1983) evaluated the water vapour budget over the Arabian Sea and showed that the evaporation and precipitation over the Arabian Sea nearly balance each other. Hence the importance of cross-equatorial moisture transport in the south west monsoon rainfall of India is emphasized.

By 1981, MONEX data sets were available and there was a spurt in the studies, on the energy budgets especially over the Arabian Sea. Nitta (1980) estimated the energy budget over Bay of Bengal and found that the magnitude of latent heat flux is generally an order higher than the heat flux. Mohanty et al (1982b) and Mohanty and Singh (1983) studied the influence of heat, moisture and moist static energy over the Arabian Sea and adjoining area on the onset and activities of the Indian summer monsoon. Their studies indicated the significant increase in the net enthalpy, latent heat energy, moist static energy and a number of other budget parameters well in advance of the onset of monsoon over Kerala coast. The vertical distribution of the budget parameters revealed that the secondary maxima of horizontal heat and moisture flux divergence observed during active monsoon period in the upper troposphere are replaced by a minimum during weak monsoon period. They also found that the cross-equatorial flow influences the intensity of
the monsoon and there was an excess of condensation over evaporation over the Arabian Sea.

Chowdhury and Karmakar (1982) examined the mean vertical profiles of atmospheric energy using MONEX-79 data. The variations of enthalpy, dry static energy and latent heat with height showed that the influx of moisture remains mainly concentrated in the lower troposphere and becomes zero by 200 mb.

Howland and Sikdar (1983), calculated the moisture budget for pre-monsoon and monsoon onset conditions in the North Eastern Arabian sea using a variety of aerological data taken during MONEX-79. They used the bulk aerodynamic method to calculate the evaporation and for moisture budget used the following equation;

\[ P = E - \int_{b}^{\infty} q V \, d\phi \]

where P is precipitation, E is evaporation and the last term is the horizontal transport of moisture. They noted that there was good increase in the specific humidity (S g/Kg), and evaporation with the onset of the monsoon. Their results also highlight the importance of cross equational moisture flux especially west of 60°E.

As in the above study, Sadhuram (1987) estimated the heat and moisture budgets of the atmosphere over the Central
Equatorial Indian Ocean. He used the flux of latent heat across the boundary walls of the area of study, evaporation and precipitation terms for moisture budget computations and sensible heat, heat due to precipitation, flux of dry static energy and radiational heating for heat budget. The time mean net flux divergence of latent heat was found to be about $-0.366 \times 10^{13}$ Cals/Sec. and that of the dry static energy $-0.471 \times 10^{13}$ Cals/Sec. He also reported that the contributions from the eddy terms are in general higher for heat budget than those for moisture budget.

Computation of the water vapour budget in a large monsoon area based on 15 years data by Oort (1985) showed that in the Indian monsoon region, the source of water vapour is Arabian Sea and the sink is North East India. It was also found that the difference between precipitation and evaporation is large and positive during April to October in a wide area over the Indian Ocean, comprising the South China Sea and Philippines.

In a recent study Sadhuram and Rameshkumar (1988) remarked that the mean rates of evaporation and precipitation over the Arabian Sea during different monsoon seasons do not vary much suggesting that the contribution of evaporation from Arabian Sea towards the moisture flux across the West coast of India is less. They also suggested that only
detailed informations on evaporation and precipitation fields over the Arabian Sea under different phases could shed more light on this problem.

Many of the above mentioned studies suggest that the cross equatorial moisture flux is an important source of moisture for the Indian Summer monsoon rainfall, although the role of evaporation from Arabian Sea is quite significant. The differences in the data, period, and techniques must be the reason for the contradictory results reported by them. Refined satellite data may prove to be a more reliable and extensive source of data. Simon and Desai (1986) using GOES and TIROS-N data successfully determined the evaporation and sensible heat values over the Indian Ocean and related them to the onset and progress of Indian Summer Monsoon.

An immense and continuous flow of energy streams from the sun. Of this, some portions of the earth receive more energy than they return to space, while others return more than they receive, but the earth system as a whole is neither warming nor cooling. Consequently, there must be a transfer of energy between various parts of this system. The role of oceans in this, is of utmost importance, as evidenced by the studies of Rao et al (1978, 1981) Basu and Parel (1984), Mohanty et al (1982a) and many others more.
Hastenrath and Lamb (1979) suggested that the hydrosphere operates, as an effective heat exporter in the northern hemisphere, equatorial belt of the Indian Ocean and the adjacent tropical seas, whereas it acts as a heat importer in the higher latitudes of the Southern Indian Ocean.

A bimodal variation in temperature and heat storage in the surface layer in a large area in the Arabian Sea was reported by Colborn (1975). Hastenrath and Lamb (1980) in another study, presented the heat budget of the Indian Ocean. They found that during the Northern summer, the radiative heat input at the top of the atmosphere and the precipitational heating of the atmosphere are much larger for the Northern Indian Ocean and smaller to the south of the Equator and vice versa during Northern winter. They also saw that the Northern Indian Ocean water body (except the more northerly region), experiences a good heat gain, during Northern winter.

Duing and Leetma (1980) computed the heat budget of the Arabian Sea during south west monsoon season and found that contrary to other geographically similar water bodies, Arabian Sea is characterised by a pronounced summer cooling. The quantum of lowering is as high as 10°C between May and July off Somalia coast and about 2 to 3°C off Indian West coast. Their study indicated that radiation overbalances the
evaporative cooling. This was contrary to the earlier findings by Colon (1962), that the evaporative heat loss would be greater than heat gain due to incoming radiation during the peak of the monsoon. Ramanadham et al (1981) studied the surface heat budget parameters using MONSOON-77 data. They found that the accumulation of energy in the surface layers of the sea encourages evaporation leading to a fall in the pressure over the region. During MONSOON-77 Rao et al (1981) found that greater evaporation has occurred along the West coast of India before the onset of the monsoon, and after the onset has set up, there is a decrease in evaporation by 30 to 40 percent.

Studies by Nuzhdin (1982) on the energetics of the atmosphere and ocean during MONEX-79 revealed that conditions which promote the onset of monsoon such as evaporation, transfer of sensible heat into the atmosphere and updrafts of warm and moist air masses are characteristic of the Central Arabian Sea whereas it was the reverse in the Western Arabian Sea. It has also been observed that lower than normal enthalpy in the Central Arabian Sea, favours the south west monsoon to set in.

Making use of the MONEX ship data for a continuous period Mohanty et al (1982a) computed the time variation of the surface energy parameters over the Arabian sea.
Murthy et al (1983) estimated the heat loss due to evaporation, back radiation and sensible heat transfer over the East Central Arabian Sea during two typical monsoon days and found that the surface heat loss accounted only about 40% of the total heat loss in the surface layer.

Rao et al (1985) using surface marine meteorological and solar radiation data collected during MONSOON-77 estimated the surface heat budget components at selected areas over North Indian Ocean. They found that energy input into the atmosphere from the ocean during disturbed weather is approximately double the corresponding value during fair-weather period.

Using satellite data Ali et al (1987) showed that the net heat gain at the ocean surface follows mainly the resultant pattern of both the shortwave radiation absorbed at the surface and the latent heat flux.

Studies by Singh and Singh (1988) on the vertical distribution of heat and momentum fluxes over the East coast of India during MONEX-79, revealed that these fluxes show remarkable changes with latitude in different layers of the atmosphere.

The above investigations reveal that the ocean-atmosphere coupling is very strong in the monsoonal Indian
Ocean. As already mentioned by Golovastov et al (1982), it has become evident that the knowledge of the interannual variability of the thermodynamics of ocean waters in the Indian Ocean is very important for developing and improving the methods of long-range prediction of weather and ocean processes.

The Indian monsoon is the most dominant feature of tropical circulations, set up and maintained by large-scale seasonal temperature differences between the ocean and the continent. Bjerknes (1966)* was the first to discuss about the temperature anomalies over the Equatorial oceans and their possible effect upon atmospheric circulation in this region. Recent evidences suggest that the variability in the intensity, frequency, inception and termination of Indian Summer Monsoon, might be associated with changes in the surface temperature of the Arabian Sea.

Saha (1970, 1974) showed that there exists a well defined zonal anomaly of SST between the equatorial West and East Indian Ocean. It was suggested that this anomaly affects the ocean atmosphere exchange and hence the low level air circulation over the Arabian Sea and therefore change the distribution of rainfall along the West coast and peninsular India.
Sastry and D'Souza (1970) found that the large spatial variations in surface temperature exceeding 11°C are due to processes such as radiation imbalance, intense upwelling off Somalia coast and complex intermingling of various water masses. Studies made by McPhaden (1975) also gave the importance of Somalia coast upwelling, offshore advection, advection of relatively cool water from the Southern Hemisphere, reduced insolation, enhanced evaporation and entrainment of thermocline water into surface mixed layer, in the evolution of SST over Arabian Sea during the South West Monsoon.

Jambunathan and Ramamurthy (1975) showed that over the Arabian Sea, the sea surface temperatures were higher than the air temperatures during active monsoon and vice versa while during weak monsoon period. Keshavamurthy et al (1975), Anjaneyulu (1981) and Shukla (1983) from their studies came to the same conclusion, that the ocean surface was relatively warmer during the months of April, May and June for good monsoon years as compared to the deficient monsoon years and it was relatively colder in the months of September, October and November. The differences in the surface temperature anomalies between good monsoon years and the deficient monsoon years for August, September and October were larger than those for April, May and June which suggest that during good monsoon years, the sea is cooled
more. Rao et al (1976) also noticed that sea surface temperatures are high during May-June while a lowering is observed in the month of July.

Fieux and Stommel (1977) analysed historic ship reports from the Arabian Sea to determine the mean variations in space and time of the SST during the onset of summer monsoon along 10°N for the period 1900-1967 and found that sea surface temperature anomalies are present but they are destroyed by the onset in May.

Sensitivity of model-simulated rainfall over India during the south west monsoon to SST anomalies over the Arabian Sea has been studied by Shukla (1975, 1976) with the GFDL model, by Washington et al (1977) with NCAR model and again by Shukla (1981) with the GLAS model. Shukla, in his earlier study, demonstrated that colder SST anomalies would increase rainfall over India. Sikka and Raghavan (1976) commented that the GFDL model does not estimate rainfall well.

Rao et al (1976) studied the thermal structure of the North West Indian Ocean in relation to the monsoon, using ISMEX 1973 data and showed that SSTs were higher in May, over Arabian Sea and that there was a decrease of SST ranging from 0.5°C in the Northern Arabian Sea to 3°C or more in the Western Arabian Sea, and a general increase in
the thickness of the mixed layer, from May to June or even July.

Saha and Bavadekar (1976) found that the correlation coefficient between the net moisture flux across the West coast of India, south of Bombay and the coastal monsoon rainfall was 0.87 and that for north of Bombay was only 0.14.

Ramage (1977) reported that observations at Canton Island and elsewhere in the tropics fail to support the idea that high SSTs cause high local rainfall. Washington et al (1977) and Druyan (1982 a,b) in similar studies using models, found that the small anomalies of sea surface temperature are able to generate only local effects. Their results showed increased (decreased) vertical velocity and precipitation over regions of warm (cold) anomalies.

Shukla and Mishra (1977) calculated the correlation coefficients between SST anomalies at about 10°N between 60° and 70°E and the seasonal mean rainfall over the Indian subdivisions. They found that the correlations between SST during July and rainfall during August over the Central and Western India were positive and significant.

Barnett (1978) tried to find the precursors of the variations in the global circulations like monsoons in sea
surface temperatures using a relatively large amount of data and concluded that they do influence each other.

Raghavan et al (1978) examined the relation between July 1964 SST in the West Arabian Sea and Indian Summer Monsoon and found that during a weak monsoon over India the sea surface experienced a significant drop in temperature over a larger area compared to that for a strong monsoon period. Weare (1979) from his studies concluded that a warmer Arabian Sea or Indian Ocean was weakly associated with decreased rainfall and increased pressure over much of the Indian subcontinent. He explained that periods of higher SSTs which is expected to lead to deeper monsoon low pressure are usually accompanied by periods of higher than average pressure over the subcontinent which would tend to offset the effects of temperature variations.

Anjaneyulu (1980) studied the monthly surface temperature at 16 representative areas over Arabian Sea for the period from 1961 to 1967 in relation to Indian monsoon activity and found that the positive anomalies of SST during May over the West and the adjoining Central Arabian Sea, though small in value were associated with subsequent good monsoon and vice versa. He also found that in good monsoon years, the difference between the highest SST during the premonsoon and the lowest SST during the monsoon in areas
off Arabia and Somalia were large and also suggested that the negative anomalies of SST during August over the Western Arabian Sea and the adjoining Central Arabian Sea were associated with good monsoon and vice versa during weak monsoon year. Ranjit Singh (1980) repeated the above calculations for the years, 1961, 1964, 1965 and 1966 and found that there was a general fall in surface temperature values ranging from 1 to 3°C during monsoon months in most of the areas.

Studies by Browen et al (1980), confirmed that the summer monsoon seasonal sea surface temperature changes are mainly influenced by mixing and heat loss at the surface.

Rao et al (1980) determined the time variation of SST and moisture over the Arabian Sea during the period from 25 May to 15 June 1973, covering the pre-onset phase of the southwest monsoon. They reported that its onset was associated with a decrease in the SST, especially north of 5°N. They also noticed a significant change in the SST and moisture distribution between the 27th and 28th and a progressive shift of the area of maximum moisture towards North East.

Studies by Joseph (1981) indicated that monsoon failures during the decade 1964-73 were followed by above normal SST over large areas of the North Indian Ocean, which
persisted for one year. He described it as a bad monsoon warms up the North Indian Ocean, through decreased upwelling along the Somalia and Arabian Coasts and weaker surface winds over the Arabian Sea and Bay of Bengal causing reduced mixing, evaporative cooling, and cloud cover. The warm sea was found to cause the formation of a warm anticyclone in the upper troposphere over the Indian seas during the following winter and the pre-monsoon seasons. This was followed by a good monsoon which lead to cooling of the North Indian Ocean.

Pisharoty (1981) studied some aspects of the relation between SST and monsoon rainfall. He suggested that medium range forecasting of some of the features of the monsoon would be feasible using the SST over the Arabian Sea.

Mishra (1981) used SST derived from the satellites NOAA-5 and TIROS-N, for a period of 3 years and observed that during a good southwest monsoon season, the cold waters from the equatorial region of the Indian Ocean advected into the Arabian Sea by early May to form the Southwest monsoon current.

Ramesh Babu et al (1981) got good autocorrelation values, for the upper part of the sea temperature values, over the North East Arabian Sea for the pre-monsoon and
monsoon period. This feature was more prominent during monsoon period.

Datta et al. (1982) from their studies on SST and moisture distribution over Arabian Sea during pre-onset and onset phase found that there is a definite indication of increase of moisture, north eastwards at the time of onset of monsoon, which is contrary to earlier findings. The onset of monsoon was also found to be associated with decrease in the SST especially north of 5°N and upto 65°E. Murthy et al. (1983) also found this lowering of SST in the East Central Arabian Sea during onset period.

Much work had been done by scientists - Kung and Sharif (1982) and Kraus and Hauson (1983) to find the possibility of using sea surface temperatures and SST anomalies in long range forecasting of the Indian summer monsoon. Later on Pathak (1982) compared the SST observations from ships and TIROS-N satellite. They found that the TIROS-N derived SST were lower than the in situ observations during MONEX period over the North Indian ocean. Barnett (1984) studied the long term trends in sea surface temperature over oceans during this century, and found that the values were contaminated by a systematic conversion from bucket to injection measurements.
Khalsa (1983) found that the maximum in SST anomaly is not correlated spatially or temporally in any consistent manner with the sum of latent and sensible heat fluxes or rainfall from high reflective clouds.

The correlation between drought and wet indices over Indian sub-continent and SST anomaly over Eastern Equatorial Pacific for monsoon and post monsoon were found to be generally significant. Studies made by Mooley and Parthasarathy (1983) show that a positive and direct correlation exists between Drought Index (IDI) and a negative or inverse correlation between wet index (IWI) for India and SST of Arabian Sea. A possible explanation given by them for this was that a warmer Equatorial Eastern Pacific would suggest upward air motion over this area and this upward moving air may ultimately compensate for decreased ascent over the Eastern Indian Ocean or the Western Pacific Ocean leading to reduced activity of the summer monsoon or a higher than average drought index for India.

Cadet and Diehl (1984) saw that warmer (colder) SST due to weaker (stronger) circulation over the Arabian sea was related to below (above) normal rainfall over India.

Gadgil et al (1984) investigated the interaction between the large scale convective system associated with the continental Inter Tropical Convergence Zone and the
ocean over which they are generated, concentrating on the relationship between organised convection over the Indian Ocean and SST. They reported that if SST, is above 28°C it is no more an important factor in determining the variability of cloudiness and also that the correlation between Western Arabian sea surface temperature and monsoon cloudiness are positive and significant. Similar studies by Rasmusson (1984), showed that the eastward movement of the SST pattern over Eastern Pacific, convective regions and subsequent monsoon rainfall in India are connected. He had brought out, that the area with SST 28°C and above migrates from north to south from August to January and that areas with SST above 28°C are associated with large scale convective clouds which also migrate in the same fashion.

According to Goswami (1984), the monsoon circulation is a result of competition between two heat sources, one located over the Indian sub-continent and the other located near the equator associated with the SST maximum there. It was also found that July SST over the Arabian sea and July rainfall are significantly negatively correlated, over Central India.

Joseph et al (1984) found that along with the monsoon rainfall over India, SST over the North Indian Ocean was found to have a 3 year oscillation.
Sastry and Ramesh Babu (1985) examined the annual variation of SST over most of the Arabian Sea and found out that it showed an anomalous bimodal pattern with higher temperatures during May and October and lower temperatures during January or February and July or August. They looked into the reasons for summer cooling of the Arabian Sea in relation to the dynamic and thermodynamic processes, and found that the surface cooling during summer in the Northern Arabian sea is due to upwelling and advection of dold water, whereas in the Eastern Arabian sea, the entrainment of cold water into the surface layer and the subsequent turbulent mixing play a dominant role.

Shetye (1984) observed that SST along the zonal strip of 9-11°N goes through four phases (i) a warming phase from approximately February to May (ii) cooling from May to August (iii) Warming from September to Mid November and (iv) cooling from mid November to January. His results also suggested that during the two warming phases the mixed layer shallows are due to detrainment and the increase in SST is predominantly due to heat gained at the surface. Cooling occurs due to detrainment of the underlying waters.

In another study, Gopinathan and Sastry (1986) indicated that significant positive correlation existed between
the extent of coverage of the warm pool in the Bay of Bengal during May and the rainfall over India during the following summer period. Kershaw (1985) reported that the use of more realistic and warmer surface temperatures especially for the East Arabian sea in models, enables a better prediction of the development of a monsoon depression, than the climatological SST. Ramesh Babu et al (1985) also studied the SST over Arabian Sea in relation to the rainfall during the monsoon period and found that they are correlated.

Further studies by Joseph and Pillai (1986), have shown that poor monsoon is able to produce a warm SST anomaly over the North Indian Ocean due to factors such as (1) reduced wind mixing (2) evaporation over the area and (3) cloud cover. This spatially large warm SST anomaly created by the poor monsoon persisted during the following October to next May.

A recent study by Ramesh Kumar et al (1986) envisages the role of Arabian Sea surface temperature on the monsoon rainfall on the West coast of India. The study showed that somewhat high and positive correlations exist between the West coast rainfall and the 27°-28°C SST range in the Eastern (Central) Arabian Sea during a good monsoon season. It should be noted here that, they used the rainfall at Goa as representing the west coast region. The main
feature of the composited SST anomaly for heavy/deficient monsoon rainfall years by Shukla (1986a) is that the differences in SST anomalies between heavy rainfall years and deficient rainfall years for August, September and October are larger than those for April, May and June.

In similar investigations, Shukla (1986) and Goswami (1986) pointed out that the results of some of the above studies using SST anomalies should be viewed with caution because, SST anomalies during pre-monsoon months are within the range of observational errors. For the above study Shukla used 75 years data whereas Goswami used 100 years data and they also calculated the correlations of SST anomaly in the North Indian Ocean. Shukla pointed out that warm (cool) SST anomaly during April, May and June was not necessarily indicative of the above (below) average monsoon rainfall, though heavy rainfall is followed by negative SST anomalies, while Goswami reported that the July SST in the Arabian sea and the July rainfall were significantly negatively correlated. His studies showed that the composite SST anomalies in the Arabian Sea for heavy and deficient rainfall years did not show any significant anomaly during the post-monsoon months.

Most of the above studies were based on simple statistical methods. Suppiah (1988) in his study on the
relationships between Indian Ocean SST and the rainfall of Sri Lanka used the Empirical Orthogonal Function (EOF) analysis for finding the spatial and temporal variation of the SST. The analyses revealed that low (high) SSTs in the previous winter months could lead to a strong (weak) summer monsoon circulation that in turn leads to a strong (weak) contrast in wind speed between the two currents of the Arabian sea. As a consequence, a strong (weak) southern current of the Arabian sea branch could bring below (above) normal rainfall over Sri Lanka and above (below) normal to the Malabar coast.

1.3 PRESENT STUDY

Many of the aforementioned studies could not adequately provide, a diurnal and daily variation of the different energy budget parameters. They had either given monthly means or averages for a period. This situation had been partially overcome, with the successful documentation of the present study. Also, although many studies had been carried out to find the relation between Arabian sea surface temperature and Indian summer monsoon rainfall, few were interested in the Indian West coast rainfall in particular. It should also be noted that, Ramesh Babu et al (1981) in their similar study had taken the rainfall of a single station, Goa, as representing the whole of West coast. The present
study incorporates rainfall of six monsoon periods for thirteen Indian westcoast stations and satellite derived sea surface temperature data to find the same relation.

1.4 DATA USED IN THE PRESENT STUDY

The data used in the present study are aerological data taken during MONSOON-77 and MONEX-79 published by the India Meteorological Department and GOSST-Comp charts published by NOAA. The surface and upper air data used are those taken at intervals of 6 hours at 00, 06, 12 and 18 GMTs by ships that were stationed in the form of polygons as shown in figure 1.1 over the Arabian Sea, during the period mentioned against each phase below. The parameters collected were dry bulb temperature, sea surface temperature, dew point temperature, geopotential height, wind speed and direction from surface upto 200 mb, for every 50 mb interval from 1000 mb. The details of the four phases are given below.

<table>
<thead>
<tr>
<th>Phase - I</th>
<th>(07.06.1977 to 20.06.1977)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Priboy</td>
<td>(12.5°N, 63.9°E)</td>
</tr>
<tr>
<td>(2) Okean</td>
<td>(14.5°N, 66°E)</td>
</tr>
<tr>
<td>(3) Shirshov</td>
<td>(12.5°N, 68°E)</td>
</tr>
<tr>
<td>(4) Priliv</td>
<td>(10.5°N, 66°E)</td>
</tr>
</tbody>
</table>
FIG. 1 MAP SHOWING THE AREAS OF STUDY.
Phase - II  (02.07.1977 to 15.07.1977)
Ships and positions same as that of Phase-I

Phase - III  (17.05.1979 to 30.05.1979)
(1) Shirshov  (6.5°N, 54.6°E)
(2) Volna  (8.7°N, 57°E)
(3) Korolev  (6.3°N, 59.1°E)
(4) Priliv  (3.9°N, 57.3°E)

Phase - IV  (02.06.1979 to 12.06.1979)
(1) Shirshov  (7°N, 64.5°E)
(2) Volna  (9.2°N, 66.7°E)
(3) Korolev  (7°N, 69°E)
(4) Priliv  (4.7°N, 66.7°E)

Hereafter in this thesis, whenever it is mentioned
Phase-I it means the period 07.06.1977 to 20.06.1977;
Phase-II means from 02.07.1977 to 15.07.1977; Phase-III
means from 17.05.1979 to 30.05.1979 and Phase-IV is from
02.06.1979 to 12.06.1979, and Polygon-I, II, III and IV
refer to the respective positions during the above four
Phases in the Arabian Sea. Sea surface temperature values
used are satellite-derived data for the months of June,
July, August and September for the years 1977, 1979, 1981,
1982, 1983 and 1984. These SSTs were computed by NOAA once
per day using an automated procedure known as Global Opera-
tional, SST computation (GOSST-Comp) as described by Brower
et al (1976). The procedure includes temperature retrievals from spectral radiance after applying statistical analysis and quality control checks to the data, correction for the effects of atmospheric attenuation by using time coincident measurements derived from Vertical Temperature Profile Radiometer (VTPR) and generation of contoured maps of the analysed SST field. They are the mean values computed for each block area of about 1° latitude and longitude. The global daily mean difference between satellite-derived SSTs and ship reports has been found to vary from 0.9°C to 0.4°C with RMS variation between 1.67°C and 2.23°C most of variance coming from ship observations. The daily rainfall for the monsoon months for the above mentioned six years were taken from the records of India Meteorological Department for the West coast stations of Trivandrum, Alleppey, Cochin, Kozhikode, Mangalore, Honavar, Panjim, Devagarh, Ratnagiri, Harnai, Bombay, Dahanu and Surat.

1.5 METHODOLOGY

The methods and the formulae used in the present study are given below. The atmospheric circulation parameters along with the budget parameters were computed for every 50 mb interval, for all the synoptic hours for which data were available.
1.5.1 Vorticity (Sec. 1)

The kinematic method was used to compute the vorticity with the help of finite difference technique.

\[
Vorticity = \frac{\Delta v}{\Delta x} - \frac{\Delta u}{\Delta y}
\]

Where \( v \) and \( v \) were the meridional components of \( E \) and \( W \) wind at east and west walls respectively and \( u \) and \( u \) the \( N \) and \( S \) zonal components at the north and south walls.

\( \Delta x \) is the length of the zonal wall and \( \Delta y \) is the length of the meridional wall.

1.5.2 Divergence (Sec. 1)

Divergence (D) also was computed using the kinematic method as follows.

\[
Divergence (D) = \frac{\Delta u}{\Delta x} + \frac{\Delta v}{\Delta y}
\]

Here, \( \Delta u = u_e - u_w \) \( \Delta v = v_n - v_s \)

Symbols have the meanings explained above.
1.5.3 Vertical Velocity (mb sec.)

The continuity equation in the isobaric co-ordinate system was used to compute the vertical velocity \( \omega \) at the different pressure levels from 1000 to 200 mb level with a 50 mb interval.

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0
\]

\[
\frac{\partial \omega}{\partial p} = -\left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = -D
\]

The divergence of the whole column of atmosphere was suitably adjusted to make the vertically integrated divergence vanish. The layer mean divergence was corrected following O'Brien's (1970) method.

where, the correction factor, $c = \frac{\int_{P_t}^{P_b} \partial_p}{\int_{P_t}^{P_b} \partial_p}$

$D_c = D - \text{Correction}$

The assumed lower boundary condition $\omega_{1000} = 0$ and upper boundary condition $\omega_{200} = 0$, is achieved by making the sum total of corrected divergence ($D_c$) between 1000 and 200 mb zero.
The vertical velocity $\omega$, at any level ($\omega_2$) is the sum of this velocity at the level just below it ($\omega_1$) and the product of corrected layer mean divergence and the pressure interval ($\Delta p$).

$$\omega_2 = \omega_1 + D_c \times \Delta p$$

1.5.4 Kinetic Energy ($m^2$ sec.$^{-2}$)

The mean kinetic energy (K.E.) was computed using the following equation.

$$K.E. = \frac{1}{2} (\bar{u}^2 + \bar{v}^2)$$

The mean values of $\bar{u}$ and $\bar{v}$ at all the levels were calculated for each polygon and used to compute mean kinetic energy. Although the mean K.E. was computed for all the levels, only those at 1000 mb, 700 mb, 500 mb and 200 mb levels are presented.

1.5.5 Precipitable Water Vapour (Kg)

The amount of precipitable water vapour (PWV) at the four ships positions were computed as follows.

$$PWV = \frac{1}{g} \int_{P_i}^{P_o} q \, dp$$
The specific humidity $q$ (Kg/Kg) was obtained using the following formula.

$$q = \frac{e}{p - (1 - e)}$$

where $e = 0.6222$

$p$ = Pressure in N/m

and $e$, the vapour pressure is computed using Tetan's formula (Murray 1967) as given below.

$$e = e_0 \exp \left[ a(T-273.16)/(T-b) \right]$$

where, $e = 6.1078$

and $T$ = Dew point temperature in degree kelvin

For $T = 263^\circ K$, $a = 21.87$ and $b = 7.66$

and

For $T = 263^\circ K$, $a = 17.26$ and $b = 35.86$

Making use of the precipitable water vapour value (PWV) at each ship position, the average for the polygon per unit area was found as follows,

$$APWV = \frac{(PWV_E + PWV_W + PWV_N + PWV_S)}{4} \times 1$$

Here the suffixes $E, W, N$ and $S$ stand for east, west, north and south. Although PWV at all the different ships were calculated, only the total value (TPWV) for the entire
polygon area is presented which is equal to APWV x area of the polygon.

1.5.6 Moisture Budget

The moisture budget equation was taken as -

\[ E - P - NMFD = 0 \]

where,

\[ E = \text{Rate of Evaporation (Kgm} \text{sec.}^{-2} \text{sec.}^{-1}) \]

\[ P = \text{Rate of Precipitation (Kgm} \text{sec.}^{-2} \text{sec.}^{-1}) \]

\[ NMFD = \text{Net Moisture Flux Divergence (Kgm} \text{sec.}^{-2} \text{sec.}^{-1}) \]

The budget parameters were calculated using the following methods.

Evaporation \((E)\) was estimated using the Bulk Aerodynamic method following Rao et al (1981) as,

\[ E = C_d \rho_0 \left( q_s - q_a \right) \nu_a \]

where,

\[ C_d, \text{the drag coefficient} = 1.6 \times 10^{-3} \text{ for } V > 13 \text{ m Sec}^{-1} \]

\[ = 1.4 \times 10^{-3} \text{ for } V < 13 \text{ m Sec}^{-1} \]

and

\[ \rho_0 \text{ the density of air, } = 1.2 \text{ kgm}^{-3} \]
Specific humidity at the sea surface was computed with Tetan's formula using SST and that at ship deck level using dew point at ship level. is the wind speed at ship deck level in m.sec$^{-1}$. Evaporation was computed for the four ship positions at every synoptic hour for which data was available. Total Mean Evaporation (TME) for the whole polygon area was computed by multiplying the mean evaporation from the four ships with the area of the polygon

i.e. $\text{TME} = (E_E + E_W + E_N + E_S) \times 0.25 \times l^2$

where, $l$ is the length of the boundary wall, of the polygon. Net Moisture Flux Divergence (NMFD) was computed as follows.

$$\text{NMFD} = \text{MF}_E - \text{MF}_W + \text{MF}_N - \text{MF}_S$$

where $\text{MF}$, the Moisture flux across the boundary wall was calculated through stepwise integration using the following equation as,

$$\text{MF} = \frac{1}{g} \int b \bar{\nu}_n \sigma \, d\phi$$

$\bar{\nu}_n$ is the average of the normal component of the wind in a layer and the other symbols have meanings same as explained before. Thus, the Moisture flux (MF) acquires the sign of the normal component of wind ($\nu_n$). By convention $\nu_n$ is positive for westerlies and southerlies. Hence if MF is positive (negative) at west and south walls and negative
(positive) at east and north walls net inflow (outflow) of moisture occurs through these walls into (out of) the polygon area. If the net moisture flux is positive (negative) it means divergence (convergence) of moisture flux from the polygon area.

Making use of the mean rate of evaporation and the net moisture flux the rate of precipitation was computed as residual. The budget parameters were computed for all the different synoptic hours of the four phases. The values of constants are those widely used in similar computations.

1.5.7 Heat Budget

The following equation was used to compute the heat budget.

\[ SH + LP + NHFD + R = 0 \]

where,

\[ SH = \text{Sensible heat flux from sea surface (watts)} \]
\[ LP = Lxp = \text{Latent heat flux due to precipitation (watts)} \]
\[ NHFD = \text{Net Heat Flux Divergence (watts)} \]
\[ R = \text{Radiative Heating/Cooling rate (watts)} \]

The method of calculations of the above parameters is discussed below in detail.
Sensible Heat (SH) = \( C_d \int_a C_p (T_s - T_o) V \)

where,

- \( C_d \), the Drag Coefficient, = \( 1.4 \times 10^{-3} \)
- \( C_p \), the specific heat at constant pressure = \( 1004 \text{J/}^\circ\text{K/kg} \)
- \( T_s \) = SST in \(^\circ\text{K}\)
- \( T_o \) = Dry bulb temperature in \(^\circ\text{K}\)

Mean sensible heat was computed for all the synoptic hours as an average of the value from the four ships. Using the mean value, the total for the whole polygon area was also computed by multiplying it with the area of the polygon.

Net Heat Flux divergence (NHFD) was found from the Heat Flux at the four boundary walls as follows

\[ \text{NHFD} = \text{HF}_E - \text{HF}_W + \text{HF}_N - \text{HF}_S \]

where, HF is calculated as,

\[ \text{HF} = \frac{1}{g} \int_{\rho_1}^{\rho_2} (C_p \bar{T} + \bar{w}) \rho \Delta \rho \, dp \]

The above integral was evaluated stepwise for every 50mb interval in the vertical. \( \rho \bar{T} \) is the mean enthalpy of the layer.

Geopotential \( \phi = g \bar{z} \)

where, \( g \) is the acceleration due to gravity and \( \bar{z} \) is the average thickness of the layer.
Similar to that discussed in Section 1.5.6, if HF is positive (negative) at west and south walls and negative (positive) at east and north walls, it is inflow (outflow) of heat to (from) the polygon area. Also if NHFD is positive (negative) it is heat flux divergence (convergence). Radiational heating is computed as the residual term.

1.5.8 Relation between SST and rainfall

As shown in the figure, the Arabian sea between 58°E to 78°E and 22°N to 8°N was divided into four quadrants viz. North West (NW), North East (NE), South West (SW) and South East (SE) and named as 1,2,3 and 4 respectively. Each quadrant was further divided into four sections and the weekly SST values at each of them were interpolated from isobars on GOSST-COMP charts. SST over each quadrant was then taken as the average of these four values. The corresponding weekly total rainfalls for the following weather stations were obtained from the records of India Meteorological Department: Trivandrum (TRV), Alleppey (ALP), Cochin (CHN), Kozhikode (KZK), Mangalore (MNG), Honavar (HNV), Panjim (PNJ), Devagarh (DVG), Ratnagiri (RTN), Harnai (HRN), Bombay (BMB), Dahanu (DHN) and Surat (SRT).

The coefficients of correlation \( r \) between the SST \( x \) and rainfall \( y \) were then computed using the following equation. (Spiegel 1961).
Where,

\[ r(x,y) = \text{Covariance } \frac{(x,y)}{(x)(y)} = \frac{1}{n} \sum (x-x)(y-y) \sqrt{\frac{\sum (x-x)^2 \times \sum (y-y)^2}{n}} \]

\[ r(x,y) = \text{Coefficient of correlation between } x \text{ and } y \]

\[ x = \text{SST at the different quadrants} \]

\[ \bar{x} = \text{mean } x \]

\[ y = \text{weekly total rainfall at the different stations.} \]

\[ \bar{y} = \text{mean } y \]

\[ n = \text{number of weeks} \]

The correlations were computed between -

(a) SST and corresponding week's rainfall

(b) SST and subsequent week's rainfall

(c) SST anomaly and corresponding week's rainfall

SSTs at all the quadrants were related to the rainfall of all the selected stations separately. The SST anomalies was found by taking the difference between the actual and normal SST values. These normals were taken from the climatic atlas of Hastenrath and Lamb (1979). The regression equations for the above cases were also developed.

Analysis and discussion of the data has been carried out in relation to the synoptic situation existed during the periods under study, which is described in the next chapter.