FINAL REPORT

THE CLIMATE TRENDS OVER SOUTH ASIA AND THEIR INFLUENCE ON SRI LANKA

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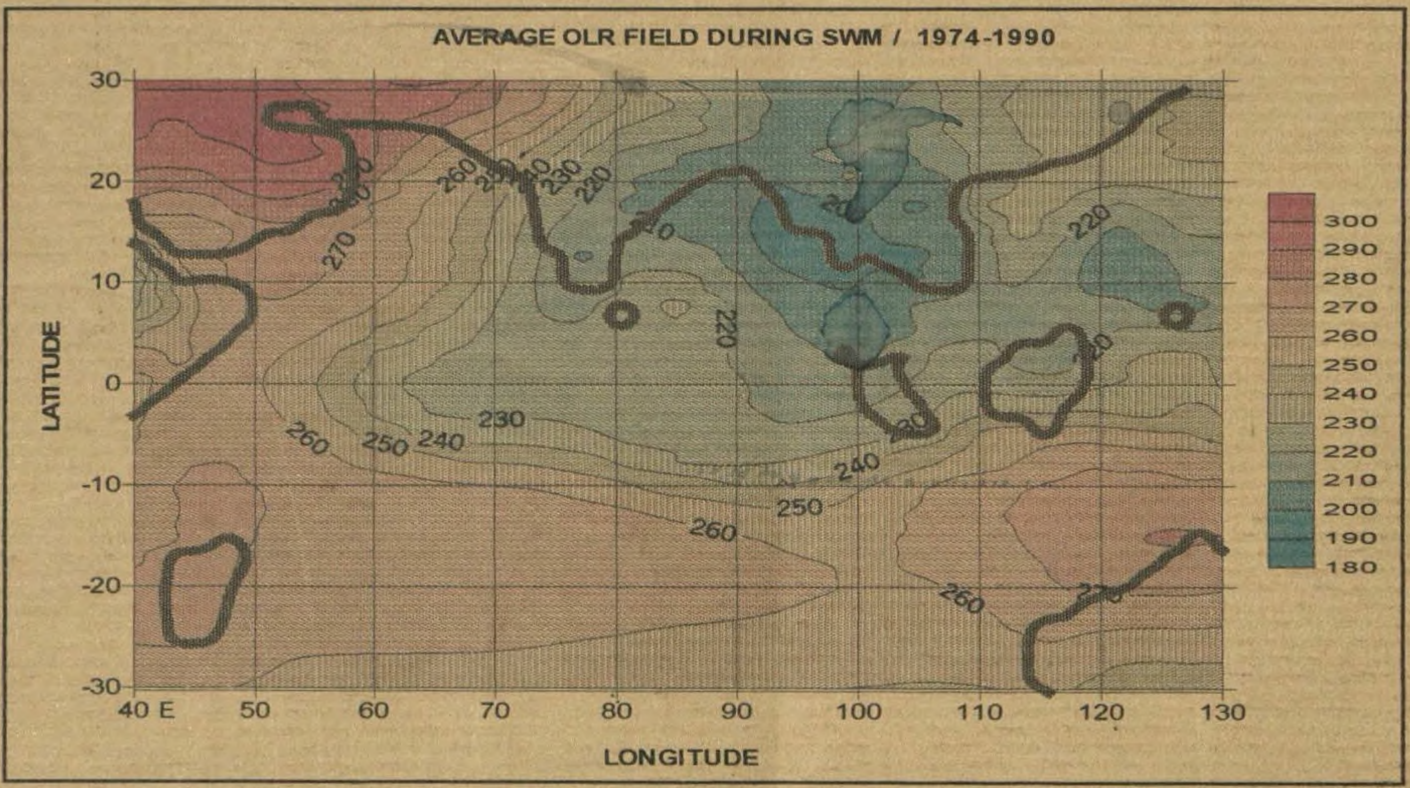
AVERAGE OLR FIELD DURING SWM / 1974-1990

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2) Description of Research Carried out

i. Introduction/ Rationale/ Justification

Earth surface receives energy from direct and scattered solar radiation. Energy from the sun passes through the atmosphere to the earth's surface. This heats earth surface and earth surface becomes the main source of energy for the atmosphere. The amount of heating varies spatially and temporally and the unequal distribution of heat leads directly to the horizontal motion we know as winds, and to the vertical motion, which creates clouds and precipitation.

Eventually the energy that has been received from the sun takes part in the various activities within the atmosphere is returned to space. Hence, the climate can be viewed as a result of series of energy transformations and exchanges within and between the atmosphere and the underlying surface.

Floods and erosions, due to heavy rainfall, can cause enormous damage to agriculture, ecology, infrastructure, and disruption to human activities. On the other hand, lack of rainfall causes drought conditions, which lead to collapse of eco-climatic system. Fluctuations in atmospheric conditions cause above/below rainfall anomalies over certain regions of the world. Sri Lanka being a Tropical Island situated at the Southern tip of the Indian subcontinent and in the Asiatic monsoon region, its climate could be characterized as tropical as well as monsoonal. As such, over Sri Lanka, air temperature varies slightly through the year, except for few mountainous areas. However, significant anomalies are found in rainfall and it has a strong impact on agricultural activities of the country.

The role of Ocean-atmosphere interactions has long been recognized as a major factor that determines tropical seasonal variability. It is generally believed that the onset and the existence of the Asiatic monsoon are primarily due to land-sea contrast. However, the fluctuations and variability of the monsoon activity may depend at least partially, on the air-sea interaction, which take place during the travel of the monsoon wind flow over the Indian Ocean, Arabian Sea and Bay of Bengal. It has been postulated that the sea surface temperature (SST) over the Arabian Sea has important influences on the monsoons flow and associated rainfall. Many researchers have pointed out that the Sea Surface Temperature around an island would have a positive influence on rainfall and other climate parameters such as temperature, Humidity and wind speed.

El-Nino phenomenon has stimulated many Oceanographic and meteorological studies in recent times, however attention is mainly focussed on the central equatorial Pacific Ocean. There are studies to indicate the effect of the Sea surface Temperature (SST) on Outgoing Longwave Radiation (OLR). Several researchers have showed the effects of OLR and SST in the Indian Ocean on rainfall of some region of Indian subcontinent

The SST over the Arabian sea has been an important factor for changes in the summer monsoon circulation and rainfall of Indian subcontinent. Since a considerable amount of moisture comes from the Arabian sea towards Asian monsoon region, it is reasonable to assume that the SST anomalies and winds over the oceanic area would have a marked influence on the weather and climate of Sri Lanka.

It is envisaged to explore the influence of SST and OLR on Sri Lankan climate. Further, an attempt will be made to elaborate relationships between OLR, SST and climatic parameters of the island.

As far as the study region in the Indian Ocean is concerned, this area is subjected to global and regional climate change and El-Nino phenomenon. The climatic variation of the study region will influence Sri Lanka and such influence will be traced by the statistical analysis of the relevant data sets of OLR and SST. The same procedure will be employed for the tracing of influence of global climatic variation on study region. Some researchers have indicated that the El-Nino signal propagates from the Indian Ocean into the Pacific Ocean. Therefore, it is worth to pay much more attention to the Indian Ocean, because of the possibility of the Indian Ocean influencing the world weather. For that reason, this study mainly focuses on SST over the Indian Ocean and their behavior during the El-Nino condition and normal conditions.

As compared to the land, Ocean has the property of storing heat. Large part of the tropics is ocean and as such oceanic region can be considered as the heat source for the atmosphere. Sri Lanka is surrounded by ocean and as such the climate and weather changes of Sri Lanka could be influence by the Indian Ocean to a greater degree. Therefore in this study sea surface temperaline variation as well as outgoing long wave radiation

(OLR) data is used to establish relationship between regional climate variation with special reference to oceanic conditions and Sri Lanka climate.

a. Monsoon and El-Nino - Southern Oscillation (ENSO)

Early studies identified the monsoon as a regional physical entity and attempted to understand its structure and variability focused on local effects. As global observations became more readily available to researchers, indications merged that the monsoon was a macro scale phenomenon, which was interactive with other global scale circulations. A number of questions remain, however, such as what is the role of the monsoon in the global climate and does the variability in the monsoon, lag, lead or occur simultaneously with the interannual variability of other phenomena.

The monsoons (Southwest Monsoon and Northeast Monsoon), which gives copious rainfall over south Asia during May to September and December to February, has three principal features that exhibit large inter-annual variability. They are the (i) quantity of monsoon rainfall during the time period. (ii) The date of onset of monsoon rains and (iii) the active break cycle of the monsoon rain.

There is also considerable evidence of tele-connection patterns between rainfall in the Northern and Southern Hemisphere, and the Southern Oscillation phenomenon (Rasmusson and Carpenter, 1983). Some researchers have indicated that the El-Nino Southern Oscillation (ENSO) signal propagates from the Indian Ocean into the Pacific Ocean.

The inter-annual fluctuations in the summer monsoon rains over Indian subcontinent have a profound socio-economic impact. Normand (1953) focussed attention to global scale oscillations in surface pressure and identified three large-scale pressure seesaws, the two Northern Oscillations and Southern Oscillation. Although, the Southern Oscillation is a global scale phenomenon, the search for useful prediction of relationships between Indian summer monsoon rainfall and Southern Oscillation continued as a major line of study.

Initially, El-Nino was considered a local climate anomaly of the eastern equatorial Pacific Ocean because of the large fluctuations in SST found there every few years. The term La-Nina refers to periods with opposite conditions to those during El-Nino events (Philander, 1990). Sumathipala (1995) have shown that there is an increase of SST over central Indian

Ocean during El-Ninos. El-Nino events occur irregularly at intervals of roughly 2-7 years, although the average is about once every 3-4 years (Quinn et al., 1987).

b. Outgoing Long-wave Radiation (OLR) and El- Nino

During the monsoon onset over India, dramatic changes in OLR were found in the large-scale atmospheric structure over the monsoon region (Krishnamurthy, 1985). Meehl (1987) analyzed the rainfall and OLR data and found that at the onset of the Northern Hemisphere summer monsoon, there was a rapid transition of cloudiness (high convective activity) and rainfall from the southwest Pacific, Australian Indonesian area to south Asia. Joseph et al., (1994) have shown that during the period 1870-1989 there were monsoon of 22 years over Kerala which suffered large delays, and 13 strong El-Ninos.

C. Sea Surface Temperature (SST) and El-Nino

The equatorial western Pacific is a region where atmospheric convective systems on many temporal and spatial scales are initiated or enhanced. It also, is the region where the world's largest reservoir of warm sea surface temperature resides. It follows, therefore, that the interaction between the ocean and the atmosphere in this warm pool region is important.

SST is very important in the tropics because horizontal thermal gradients are weak and the atmosphere is very sensitive to the oceanic and continental surface conditions. Many studies have related the rainfall variability in the tropical areas to SSTs. The observed variability by Tropical Ocean Global Atmosphere (TOGA) also suggests a possible connection between El-Nino and global warming. According to TOGA study average SSTs in the tropical Pacific were unusually high during the 1980s and 1990s.

The influence of SST over the Arabian sea has been an important factor for explaining the changes in the summer monsoon circulation and rainfall over India (Saha et al., 1973, Saha,1974). Since a considerable amount of moisture comes from the Arabian sea, it is reasonable to assume that the SST anomalies and wind over the oceanic area influence the weather and climate of India and Sri Lanka. Suppiah (1996) using rainfall and Southern Oscillation Index (SOI) data for 110-year period from 1881-1990 found correlation between Sri Lankan rainfall and SOI in decadal scale fluctuation. Particularly major change in the temporal correlations has occurred during the Southwest Monsoon (SWM) season around 1900, 1930 and 1960.

Angell (1981) correlated summer monsoon rainfall over India with the average SST and found a significant correlation between summer monsoon rainfall and SST anomalies during the following December – January. Philander (1985) has shown that a weaker / stronger than normal Asian summer monsoon is very favorable for triggering the El-Nino / La-Nina state of the equatorial Pacific. Rasmusson and Carpenter (1983) examined the relationships between eastern equatorial Pacific SST anomalies and rainfall over India and Sri Lanka. They demonstrated a negative relationship between the SST anomalies and Indian summer monsoon and a positive relationship between SST anomalies and Sri Lankan autumnal rainfall.

As reported in earlier studies by Ramage (1971), Ramage (1974), Manabe et al., (1974), Shukla (1975), Shukla and Misra (1977), Weare (1979), negative SST anomalies over the Arabian sea could strengthen the high pressure over oceanic area and consequently cause a strong pressure gradient between the Arabian sea and central India and therefore lead to strong summer monsoon circulation. Rowell (1991) has shown that the Arabian regions SST have a clear relationship with rainfall of the Indian sub-continent

d. The Climate and Climate Impacts on Sri Lanka.

Sri Lanka is a humid tropical country, situated on the path of two monsoons, the Southwest Monsoon and the Northeast Monsoon. Despite of this favorable position, extensive areas are water deficit and a considerable portion of the country experiences dry condition for several months. The western Wet Zone is the only water surplus area in the country; acute deficit areas exist in the northern, north western, north eastern and southeastern zones. The availability of surface water in the Dry Zone is frequently affected by the failure of the Northeast Monsoon.

The literature on the SST anomalies and OLR fluctuation over Sri Lankan region is scanty and not well documented. However, Rasmusson and Carpenter (1983), Shukla (1975, 1977), Suppiah (1984 I, 1984 II, 1987, 1988, 1989, 1993, 1996, 1997) examined the relationships between the eastern equatorial Pacific SST anomalies and rainfall over India and Sri Lanka.

Although their results are inconclusive, some studies indicate a trend of rainfall decreases in the hill country, particularly in the Nuwara-Eliya district. It is likely that these are cyclical changes. In the Dry Zone, although there is no evidence of significant continuous decline in rainfall, the frequency of drought years seems to have increased more over the last three decades than during the first half of the century .

Sri Lanka has experienced weather related immemorial disasters such as floods and droughts. The country experiences effect of depressions and storms which form over the southern half of the Bay of Bengal mainly in October, November and December.

Due to above reasons it is worth to pay much more attention to the Indian Ocean, because of the possibility of the Indian Ocean influence on the world weather. For that reason, this study mainly focuses on the Indian Ocean climatic parameters and their behaviours during the El-Nino and normal conditions.

ii. Objectives

The Main objectives of the study can be synthesize as follows;

a. The study aims to find the influence of SST and OLR anomalies in the Indian Ocean, on rainfall distribution pattern of Sri Lanka.

b. Spatial and temporal fluctuation of SST and OLR in the Indian Ocean and their relationship to El-Nino.

c. The relationship between El-Nino and Rainfall fluctuation in Sri Lanka.

In the proposed study an emphasis will be placed on the relationships between the rainfall of Sri Lanka and SST, OLR variations in the Indian Ocean and Western Pacific Ocean. It is hoped to employ the appropriate statistical procedures to reveal the less known aspects of the Indian Ocean SST, OLR and western Pacific SST with the Sri Lankan rainfall.

iii. MATERIALS AND METHODS

a. Global OLR data set

Researchers often use Outgoing Longwave Radiation (OLR) as an indicator of temporal and spatial characteristics of large-scale convective activity (Murakami and Nakazawa 1985, Sumathipala and Murakami 1986, Sumathipala 1989). OLR from the Earth tends to be dominated by either the radiation from the surface where there are no clouds or from cloud tops. So it serves as a proxy index of the amount of convection in the tropics (Morriisey 1986)

A global data set of Outgoing Longwave Radiation (OLR) was obtained from the Department of Meteorology, University of Hawaii. The data consist of monthly mean values at grid spacing of 2.5^{0} x 2.5^{0} Latitude and Longitude resolution. The data cover the period from June 1974 to October 1990 with a gap from March to December 1978.

Outgoing Long wave Radiation (OLR) data with the 2.5^{0} x 2.5^{0} degree resolution was obtained from the global databases. The data relevant to the Indian Ocean, covering Latitudes 30^{0} N to 30^{0} S and Longitudes 40^{0} E to 120^{0} E were extracted from the above databases and compiled in suitable format. Study area covers the Indian Ocean and that was divided into thirteen sub-regions Fig.1 and Table-I. The anomaly values for each region were calculated by subtracting the long-term average monthly value from the individual monthly values. These anomaly values were used to plot time series and trends. OLR field of several regions were used to calculate the simultaneous and lag correlation coefficient with the SWM / NEM rainfall in Wet/Dry zone of Sri Lanka.

Table-I Selected 13 sub-regions in the study area.

Site Region	Latitude	Longitude
AS	15° N - 25° N	55° E - 75° E
A	10° N - 0° EQ	50° E - 77.5° E
B	0° EQ - 10° S	50° E - 77.5° E
C	10° S - 25° S	50° E - 77.5° E
SL	15° N - 5° N	77.5° E - 82.5° E
D	5° N - 15° S	77.5° E - 95° E
E	15° S - 25° S	77.5° E - 95° E
F	10° N - 0° EQ	95° E - 110° E
G	0° EQ - 10° S	95° E - 110° E
H	22.5° N - 5° N	110° E - 120° E
I	5° N - 10° S	110° E - 120° E
J	10° S - 25° S	100° E - 120° E
K	22.5° N - 5° N	80° E - 100° E

OLR data set used for the analysis

Data set	Category	Duration	Study area
A	OLR values in an El-Nino years	1974 to 1990	30°N-30°S , 40°E-30°E
B	OLR values in La-Nina years	1974 to 1990	30°N-30°S , 40°E-30°E
C	OLR values for normal years	1974 to 1990	30°N-30°S , 40°E-30°E
D	Rainfall values in an El-Nino years	1974 to 1990	Wet zone and Dry zone
E	Rainfall values in La-Nina years	1974 to 1990	Wet zone and Dry zone
F	Rainfall values in normal years	1974 to 1990	Wet zone and Dry zone

Data sets A and C were used to plot monthly mean spatial patterns of the OLR in the Indian Ocean during an El-Nino year and a Normal year. Data set A, B and C were used to correlate with rainfall data (data sets D, E and F) in Wet zone and Dry zone during El-Nino, La-Nina and normal years. To derive a rainfall index value for the Wet zone and Dry zone annual cycle and long-term cycle was eliminated from each rainfall stations. This normalized rainfall index were correlated (simultaneously and with one month lag) with the grid point OLR field of the study area to calculate the correlation coefficients. These calculated values were used to plot monthly mean spatial correlation patterns in the Indian Ocean during El-Nino year, La-Nina and normal year.

OLR data of the following regions were used for the time versus Longitudes and time versus Latitudes plots.

Region	**Location**	**Duration**
X	30° N - 30° S, 70° E - 90° E	1974 to 1990
Y	30° N - 30 °S, 90° E - 110° E	1974 to 1990
1	20° N - 0°, 50° E - 110° E	1974 to 1990
2	0° - 20° S , 50° E -110° E	1974 to 1990
3	10° N,10° S, 50° E,110° E	1974 to 1990

According to Fig.2, average OLR for the NEM period shows active convective region (OLR < 220Wm^{-2}) located in the area between Latitudes 5° N to 10° S and Longitudes East of 100° E towards the Pacific Ocean.

b. Global SST data set:

A global data set of Sea Surface Temperature (SST) was obtained from the Climate and Marine Department of the Japan Meteorology Agency. The data consist of monthly mean values at grid spacing of 2° x 2° Latitude and Longitude resolution. The data set is available for the years from 1971 to 1990.

SST data from the following regions were used to calculate the correlation coefficient (simultaneous and with lag) with the rainfall data in Dry/ Wet zone during SWM/NEM period.

Region	**Location**
RX6	3° N - 3° S, 51° E - 61° E
R4	7° N - 11° N, 49° E - 53° E
RX2	3° S - 7° S, 41° E - 47° E
R1	15° N - 25° N, 51° E - 57° E
R2	15° N - 21° N, 85° E - 91° E
RC	5° N - 9° N, 97° E - 103° E
RE	3° S - 7° S, 107° E - 113° E

The El-Nino years and La-Nina years were taken from Suppiah (1993,1997). These specific periods were chosen from May of an El-Nino or La-Nina year to April of the following year. Long-term mean and annual cycles were removed from each grid point data.

El-Nino years were 1972/73, 1976/77, 1982/83 and 1986/87 while La-Nina years were 1975/76 and 1988/89.

Data set	**Category**	**Duration**	**Study area**
SSTE	SST values in an El-Nino years	1971 to 1990	29° N - 29° S, 41°E -129° E
SSTL	SST values in La-Nina years	1971 to 1990	29° N - 29° S, 41°E -129° E
SSTN	SST values for normal years	1971 to 1990	29° N - 29°S, 41°E - 129° E

These SST data were used to plot time versus Longitudes and time versus Latitudes sections.

Region XX and YY consist some continent data points and they were eliminated from the data set before the analysis was carried out.

Region	**Location**	**Duration**
XX	25° N - 19° S, 41° E - 79° E	1971 to 1990
YY	9° N - 9° S, 41° E - 129° E	1971 to 1990

Table-2. Selected locations for SST in the study domain for the Spectral and Harmonic analysis

Site Region	**Location**	**Zone**	**Latitude**	**Longitude**
R1	NH	WS	21° N – 25° N	51° E - 57° E
R4	NH	WS	7° N – 9° N	49° E - 53° E
RX1	NH	WS	5° N – 9° N	65° E - 69° E
R2	NH	ES	17° N – 21° N	85° E - 91° E
RY1	NH	ES	11° N – 15° N	123° E-129° E
RY2	NH	ES	5° N - 9° N	81° E - 85°E
RY3	NH	ES	7° N – 11° N	97° E -103° E
RX2	SH	WS	3° S – 7° S	41° E - 47° E
RX3	SH	WS	3° S – 7° S	75° E - 79° E
RY4	SH	ES	3° S – 7° S	81° E - 85° E
RY5	SH	ES	3° S – 7° S	107° E-113° E
RX4	SH	WS	13° S – 17° S	53° E - 57° E
RX5	SH	WS	13° S – 17° S	71° E - 77° E
RY6	SH	ES	13° S – 17° S	93° E - 99° E
R9	SH	ES	13° S – 17° S	111° E-117° E
R11	SH	WS	23° S – 27° S	73° E - 79° E
R12	SH	ES	23° S – 27° S	93° E - 97° E
Equator	Equator	WS	1° N – 1° S	51° E - 69° E
1Gad point	NH	WS	7° N	79° E

SH - Southern Hemisphere, NH - Northern Hemisphere, WS - Western Side, ES - Eastern Side

The study area covered the Indian Ocean from Latitudes 29° N-29° S and 41° E-129° E Longitudes. In this domain selected areas were subjected for the Harmonic Analysis and Spectral Analysis. Fig.3 shows the selected areas and table-2 shows the selected locations throughout the study area. Each area consists of at least 9 point data. In this investigation, normalized values of SST data were used in all calculations, for each grid point data long term and annual cycle were removed from the raw data. Spectral analysis was performed to reveal the principal modes of monthly SST for the selected regions in the study domain. Using results of spectral analysis, major spectral lines were identified. The study included 19 selected regions spread throughout the area and nine regions located in the belt of 10° N, 10° S Latitudes and 41° E-129° E Longitudes.

c. Rainfall data set

The basic rainfall data set used in this study consists of monthly mean rainfall values of 14 stations spread over the country, for the years 1901 to 1996. The data for 1901 to 1980 were obtained from the publication of Yoshino and Suppiah (1982) and rest were obtained from the Department of Meteorology, Colombo, Sri Lanka.

The major rainfall stations considered in the study are;

Colombo
Galle
Kandy
Nuwara-Eliya
Ratnapura
Diyatalawa
Anuradhapura
Maha-Iluppallama
Hambanthota
Batticaloa
Trincomalee
Kurunagala
Matara
Bandarawela

The basic rainfall data set used in this study consists of monthly mean rainfall values of 12 stations spread over the country, for the years 1901 to 1996. There were 23 El-Nino years during this period. The rainfall data for El-Nino and La-Nina years were extracted separately form the rainfall data set and these were named as data set A and data set B. The rainfall data of normal years were named as data set C. Average monthly values for El-Nino/ La-Nina year and normal year were calculated from these data sets.

Then using rainfall data for each month (i), and for each station (j), for El-Nino year and normal year an Index (I) was computed as follows

$$I_{ij} = \{(\text{El-Nino}_{ij} - \text{Normal}_{ij}) / \text{Normal}_{ij}\} \times 100$$

$$I_{ij} = \{(\text{La-Nina}_{ij} - \text{Normal}_{ij}) / \text{Normal}_{ij}\} \times 100$$

Where i varies from 1 to 12 and j has values 1 to 12. Monthly values of I_{ij} were plotted to study the rainfall variation pattern

Twelve major rainfall stations spread through out the country were used to investigate the behaviour of rainfall fluctuations during El-Nino and La-Nina years from 1974 to 1994. During this time period there were five El-Nino (76/77, 82/83, 86/87, 91/92, 92/93) events and two La-Nina (75/76, 88/89) events. The El-Nino and La-Nina years were taken from Vincent et al.,(1998). The rainfall data of the two events (El-Nino and La-Nina) were eliminated from the original rainfall data set. These data sets were named El-Nino, La-Nina and Normal for further analysis. These three data sets (El-Nino, La-Nina and Normal) were used to plot the time series of rainfall fluctuations of twelve stations (individually) spread through out the country. For these plotting the long term mean and mean annual cycle were removed from the raw data for each rainfall station.

Monthly rainfall data of 12 stations for the period from 1900 to 1996 were used for the investigation. From the 12 stations, six stations are located in the Wet Zone and other six stations are located in the Dry Zone Fig.4. Monthly rainfall data of the respective stations was subjected to Power Spectrum Analysis and Harmonic Analysis. Here, the total number of observations is 96 x 12 and the lag was chosen as large as possible but not exceeding one fifth of the total number of data points i.e. number of months. The data were subjected to Power Spectrum analysis to find out the major spectral peaks during the 96-year period from 1900 to 1996. These major spectral lines were eliminated using Harmonic analysis (low pass Butter worth filter technique). Harmonic Analysis was used to study the behavior of regional rainfall fluctuation during the period.

d. Methods of analysis

In the proposed study an emphasis was placed on the relationships between the of Sri Lanka, SST and OLR variations in the Indian and Western Pacific Ocean. Following statistical analysis procedures were used to reveal the less known aspects of the Indian Ocean SST, OLR and western Pacific Ocean SST with the Sri Lanka rainfall.

Time Series Analysis.

This analysis could be dealt with temporal aspects of the relationships between El-Nino rainfalls over the island.

Spatial and Temporal correlation analysis.

During this analysis an attempt was made to understand the correlation between the OLR and SST in relation to the geographical space.

Lag-Lead Correlation analysis:

This analysis was use to examine the temporal correlation of OLR and SST with time lags.

Spectral Analysis:

This analysis was use to trace the principal oscillation modes of SST, OLR and Rainfall.

Harmonic Analysis:

This analysis was use to filter the unnecessary noises of the raw data (SST, OLR and Rainfall) and identify the major trends of SST, OLR and Rainfall

Harmonic analysis using least square method

The process of decomposition of periodic motions into its components is called *harmonic analysis* and the components are called *harmonic constituents.* Any waveform can be analysed as a combination of sine waves of various amplitude, frequency and phases; the method is called a ***Fourier analysis.*** The motion is expressed as sum of sine and cosine functions of known frequencies; such a sum is known as a *Fourier* series. For example, any kind of periodic motion, η, can be expressed as $\eta(t) = \sum_{k=1}^{K}(a_k \cos\omega_k t + b_k \sin\omega_k t)$, where ω_k represents the frequency of the kth constituent. Solving the equations will result in values for *a* and *b* for each constituent.

The solution minimises the difference between the observed, η_n series and calculated series data according to $\sum_{0}^{N}(\eta_n - \sum_{k=1}^{k}(a_k \cos\omega_k t_n + b_k \sin\omega_k t_n))^2$. The $\sqrt{a^2 + b^2}$ is the amplitude of the constituent. The phase, θ, is calculated from $2\pi\theta$ = arctan(a/b).

To extract the constituents, long periods of records are required, in order to obtain a reliable separation of constituents. Some constituents have periods close to each other. The longer the time series, the more constituents can be fitted. The longest records were 1152 month in rainfall, 185 months for OLR and 240 months for SST Longer records imply higher accuracy in determination of the constants.

To find a and b constituents procedure mentioned below is applied.

$$f(a,b) = \sum_{n=0}^{N} (h_n - (a\cos\omega t + b\sin\omega t))^2 = \text{minimum}$$

$$aA_1 + bB_1 = C_1 \qquad aA_2 + bB_2 = C_2$$

$$\frac{\partial f}{\partial a} = 0 \quad \frac{\partial f}{\partial b} = 0.$$

$$\frac{\partial f}{\partial a} = \sum_{n=0}^{N} -(2\cos\omega t_n (h_n - a\cos\omega t_n - b sin\omega t_n)) = 0 \qquad \sum_{n=0}^{N} (a\cos^2\omega t_n + b sin\omega t_n \cos\omega t_n) = \sum_{n=0}^{N} h_n \cos\omega t_n$$

$$\frac{\partial f}{\partial b} = \sum_{n=0}^{N} -(2\sin\omega t_n (h_n - a\cos wt_n - b sin\omega t_n)) = 0 \qquad \sum_{n=0}^{N} (a\sin\omega t_n \cos\omega t_n + b sin^2\omega t_n) = \sum_{n=0}^{N} h_n \sin\omega t_n$$

$$a \overbrace{\sum_{n=0}^{N} \cos^2\omega t_n}^{A_1} + b \overbrace{\sum_{n=0}^{N} sin\,\omega t_n \cos\omega t_n}^{B_1} = \overbrace{\sum_{n=0}^{N} h_n \cos\omega t_n}^{C_1}$$

$$a \overbrace{\sum_{n=0}^{N} \sin\omega t_n \cos\omega t_n}^{A_2} + b \overbrace{\sum_{n=0}^{N} sin^2\omega t_n}^{B_2} = \overbrace{\sum_{n=0}^{N} h_n \sin\omega t_n}^{C_2}$$

$$aA_1 + bB_1 = C_1 \qquad aA_2 + bB_2 = C_2$$

$$a = \frac{C_1B_2 - C_2B_1}{A_1B_2 - A_2B_1} \qquad b = \frac{C_1A_2 - C_2A_1}{A_2B_1 - A_1B_2}$$

Spectral Analyses (SPA)

$$f(a,b) = \sum_{n=0}^{N} (h_n - (a\cos\omega t + b\sin\omega t))^2 = \text{minimum}$$

Any simple cyclic pattern consists of specific amplitudes, periods and hases.

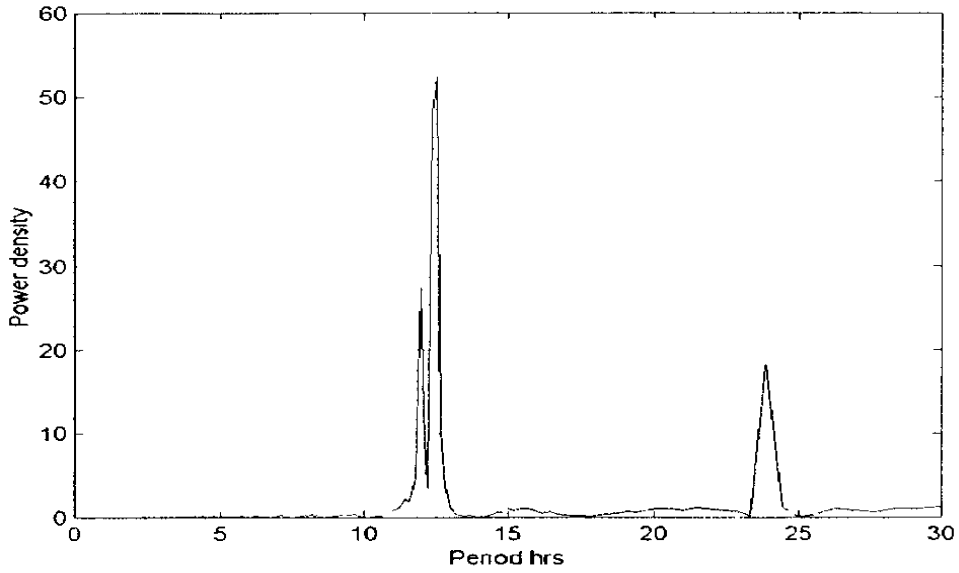

Fig.5 shows the SPA result

Analysis was carried out by using Matlab software, Version 5.2, 1998

Spectral analyses (SPA) can be used to find dominant frequencies from time series of records without prior knowledge of expected periods. Spectral analysis method consisted of applying a ***Fast Fourier Transform*** (FFT) on the autocorrelation function. *Fast Fourier Transform Algorithm* is available as a built in function in Matlab software, called 'FFT' was used to develop spectral analysis program. The Power Spectrum Density (PSD) is an outcome of this SPA, where the magnitude of PSD is large for dominant frequencies.

IV. Result and Discussion

1. OLR Field

1.a. Monthly Standard Deviation of OLR in the study area

Standard deviation (STD) and spatial correlation pattern of the OLR field for the study region were plotted. These STD plotting shows a high variation of OLR field (STD > 7 Wm^{-2}) is located in the Eastern side of the study area spreading towards the Indian sub-continent including Sri Lanka. Further, there is an area with high variation of OLR field located over the Arabian continent and Pakistan. In the Southern part of the Ocean, there is an area between Latitudes 7.5^{0} S to 15^{0} S Longitudes 65^{0} E to 77.5^{0} E having a high variation (STD > 7 Wm^{-2}) of OLR throughout the year. Most prominently high variation of OLR occurred in the maritime continent area.

The variation of monthly OLR field around Sri Lankan area shows high variation, which occurs during the months of November and March. By comparing these two months (November and March) November variation is higher than that of March. The map of average wind field by Sadler et al., (1987) indicates that in the month of March winds blow from the Bay of Bengal towards Sri Lanka with a magnitude of 2 m/s. In the month of November it rises up to 4m/s.

In March, the high OLR variation is located south of Sri Lanka. Further it spreads towards the Southern Hemisphere and over to the Malaysian region. This indicates that these areas have high variability in convective activity during March. After the month of March the high variation of OLR field begins to propagate in the Northwest direction. In the month of June it is located in the equatorial north Arabian Sea and over the Indian subcontinent and Western North Pacific. These findings are well in agreement with Sumathipala and Murakami (1986). This indicates that those areas have intense convective activity and also these areas supply substantial amount of energy to the atmosphere.

During NEM period from December to February the variation of OLR field is developed in the Bay of Bengal. During this period higher fluctuations (high STD) of OLR fields is dominant in the Sri Lanka area. According to Suppiah (1989), during NEM period, above-normal rainfall anomalies are caused by tropical depression and cyclones that originate in the Southern part of the Bay of Bengal that strike Sri Lanka.

1.b. Behaviour of OLR field during Southwest Monsoon (SWM) and Northeast Monsoon (NEM) periods

The OLR data were analyzed and mapped to obtain the large-scale pattern of radiation field. In this analysis the data were grouped into four seasons as Southwest Monsoon (SWM) May to August, Northeast Monsoon (NEM) November to February and two Inter-monsoons, March – April and September - October. At the beginning of the study emphasis was placed on the two monsoons.

Seventeen year (1974 - 1990) OLR data were analyzed for the region (30^o N - 30^o S, 50^o E-120^o E) and the average values for the southwest monsoon period is shown in Fig.6 Active convective region (low OLR values) is located around (15^o N, 95^o E) in the northeastern Bay of Bengal. The axis of low OLR runs along the monsoon trough. This supports the idea that the OLR can be used as a parameter for convective activity (Morrisey 1986). OLR lower than 240 Wm^{-2} is considered to be representative of cloudy areas. Therefore Sri Lanka region with OLR values between 220-230 Wm^{-2} can be identified as cloudy. When OLR values of individual years are analyzed, the distributions during most of the years are close to the long-term average for

SWM season. But some years indicate a substantial deviation from the long-term average.

OLR is a parameter that can be used to identify large-scale convective activity (Sumathipala and Murakami 1986, Sumathipala 1989). Sumathipala 1989 has used OLR effectively to show the difference in cloud cover and the rainfall between two inter-monsoons of Sri Lanka.

1.c. Behavior of OLR field during El-Nino year.

In this analysis, special attention was paid to El-Nino years. According to accepted definition there were 3 El-Nino events during this 17-year period. Out of the three, 1982 El-Nino was the strongest one while 1976 and 1987 El Nino were mild El-Nino according to global variations Philander (1985, 1990).

1.c.1. Southwest Monsoon (SWM) period

During 1976 there was a very clear high OLR field (> 260 Wm^{-2}) around Sri Lanka. This indicates very dry conditions during 1976 SWM period. Even over Indian and the North Bay of Bengal low OLR region has reduced in extent. According to OLR field Southwest monsoons of 1982 and 1987 are little different from the average condition. Condition prior to 1976 SWM show substantial deviation from the average situation. The active area (low OLR) seems to be separated into two centers; one to the Northwest of Sri Lanka over Indian Ocean and other towards east of normal low OLR centre. This must be due to sub-scale systems developing within the monsoon domain.

Saha (1974), Saha et al., (1973) have shown that, air-sea interactions over the Arabian sea is considered to be one of the important factors in explaining the fluctuations in the intensity of the monsoon circulation and the associated rate of precipitation over India and surroundings.

OLR over Arabia has recorded high value (>300 Wm^{-2}) during 1976, 1982, and 1987, which may be due to strong subsidence in the area. It seems that north south over turning in a small scale has strengthened in Sri Lanka area and circulation pattern resembles a break monsoon character. During 1985 and 1986 prior to 86/87 El-Nino, development of high OLR region can be observed over the Indian Ocean around Sri Lanka. Suppiah (1989) has found that large-scale signals appear in wind anomalies over Sri Lanka prior to El-Nino - Southern Oscillalices (ENSO) events. The upper level Easterlies (Westerlies) and weak (strong) low level Easterlies are dominant in March before the La-Nina (El-Nino) years and these wind anomalies persist until the ENSO events reach maturity. When the OLR field pattern of the three El-Nino events are considered together, 1982/83 was a major El-Nino. The OLR patterns are different SWM when compared to 1976/77 and 1986/87 El-Nino events during. Thus 1982/83 had a different character in the flow pattern and OLR in the region.

1.c. 2. Northeast Monsoon (NEM) Period

In the long-term average the axis of high OLR field is located around 17^{0} N Latitudes in the Indian region. Low OLR values and thus convective activity is confined to north Australia-Borneo-Malaysia region. Over Sri Lanka the average value of OLR for the NEM period is around 260 Wm^{-2}. This is understandable because convective activity and rainfall over Sri Lanka during NEM is less than SWM.

During the two-year period prior to 1982 El-Nino, OLR field to north of Sri Lanka showed gradual change from the average. Area of OLR greater than 270 Wm^{-2} shifts westward from the Bay of Bengal in 1980 Fig.7 and in 1981 Fig.8 towards the Arabian sea. Suppiah (1989) has found that during the early stage an El-Nino event, the Inter Tropical Convergence Zone (ITCZ) is usually weak and located far south of its mean position and thus give ample or no rainfall to Sri Lanka During El-Nino years. 270 Wm^{-2} area extends over to Sri Lanka and it indicates dry conditions during this period. During NEM of 1985, the OLR field over Sri Lanka is around 250 Wm^{-2} which indicates lack of convective activity.

1.d. OLR fluctuation in sub-regions of the study domain

Regions (AS, A, B) located in the Indian Ocean showed strong convective activity during the SWM period. During NEM period regions in the Eastern Indian Ocean (K, F, G and I) showed high convective activity. The normal annual cycle of OLR of the region in Western Indian Ocean and Eastern Indian Ocean showed an opposite phase relationship. Basically, highest convective activity occurred during the NEM period and low convective activity occurred during SWM period. This indicates a fluctuation of convective activity between the East and West Indian Ocean.

Normal annual cycle of OLR of regions A and AS in the western Indian Ocean shows high convective activity (OLR $<$ 240 Wm^{-2}) in the SWM period and low convective activity (OLR $>$ 240 Wm^{-2}) in NEM period. The region B shows high convective activity during the SWM period and low convective activity during two Inter-monsoons. The comparison of the regions A and C reveals that the region C shows the opposite OLR activity. In the region C high convective activity occurred during the SWM period and low convective activity occurred during NEM period. Further, a decreasing trend of OLR during the eighties is evident in the region C. The eastern side of Sri Lanka

(Region E, F, G, H, I) shows high convective activity during both Inter-monsoon periods and the NEM period. The OLR value below 240 Wm^{-2} represents high convective activity in regions F, G and I throughout the year Fig.1.

Regions AS, A, B, K, H, G and I are in the monsoon domain and region F, G and I show higher convective activity in the two Inter-monsoon periods than in the SWM period. This indicates higher convective activity and possible higher rainfall in the Inter-monsoon periods over these regions. Sumathipala (1989) dealing with Sri Lanka rainfall data has showed that Sri Lanka records the highest rainfall intensity during the inter-monsoon periods rather than Summer Monsoon period. Suppiah (1989) also mentioned that the wettest season is the second inter-monsoon period.

OLR anomalies and mean annual cycle for each region were plotted. From these OLR anomalies in region E and I, it is clear that there are signals, which related to the El-Nino phenomenon Fig.9 and Fig.10 During El-Nino years region E shows high convective activity (OLR < 240 Wm^{-2}) and Region I shows low convective activity (OLR>240. Wm^{-2}). This is due to strong upward vertical motion in region E and strong downward vertical motion (sinking area) in region I.

Regions E and I are interesting because these regions show strong peak in OLR anomalies during the El-Nino years in 1976/77, 1982/83, and 1986/87. Further, these regions show an alternation of OLR anomalies. The OLR increases in one region and decreases in the other simultaneously during the El-Nino year Fig.9 and Fig.10. This may indicate that Indian Ocean had some connection with factor that create El-Nino. The wind data analysis by Sumathipala and Murakami (1986 and 1988) has shown that Indian Ocean has direct connection with the El-Nino phenomenon.

1.e. Correlation of OLR and rainfall during SWM and NEM period.

In order to see the influence of OLR field on the SWM and NEM rainfall of Sri Lanka correlation studies were conducted in regions in the western Indian Ocean (OLR field) with the SWM rainfall in the wet zone. The same procedure was carried out for the NEM period for the Dry zone rainfall with the regions located in the eastern Indian Ocean (G, K, D, I, J, F and SL). During SWM period highest correlations were found with a significant level $p < 0.05$ for the regions A, B and D with a one-month lag (Table-3). Further, significant correlations were found with a 3-month lag for the region B and C.

The average monthly rainfall values of the South West Monsoon (SWM) period 1974 to 1990 for four stations (Colombo, Ratmalana, Katunayaka, Galle) in wet zone were calculated. These calculated rainfall values were used to calculate correlation coefficients between OLR in the sub regions with lags. The same procedure was applied for the Northeast Monsoon (NEM) period, for the four stations Trincomalee, Badulla, Vavuniya, and Anuradhapura (in Dry zone). Correlation between OLR of the certain sub regions in the Indian Ocean and rainfall in Sri Lanka for the SWM and NEM period are significant.

For the SWM period, rainfall is highly correlated with the regions C, J, H and E. However, among these regions H and J are located in the eastern side of the Indian Ocean. These regions show high convective activity during SWM period and these findings are in agreement with the findings of

Sumathipala (1989). These regions indicate that there is a tele-connection between OLR and the rainfall of SWM period.

During the NEM period highest negative correlation coefficient were found in the regions K and H with a one-month lag. It is noteworthy to point out that the region K showed negative correlation with lag1, lag2, and lag3 time period (OLR leads 1, 2 and 3 months respectively). Highest correlations were found before the 3-month of the NEM onset in the region (Table-4). This indicated that this region should be an active convective region during the NEM period and this is well experienced in the regions including Sri Lanka with frequent storms and heavy rain. Further, negative correlations were found with the OLR field over Sri Lanka during NEM period. But region H showed the highest correlation with one-month lag.

During the NEM period, all the regions show significant correlation between the OLR and rainfall. Throughout the NEM period region A, B, C, and H, which are situated in the western Indian Ocean, show highly significant correlation with the rainfall. Therefore, it is very important to trace the relationships between the OLR field in these regions for further analysis.

1.f. Behavior of OLR over the Indian Ocean during an El-Nino and Normal year.

In January during normal year the high convective area is located over the maritime continent and gradually moves north-westward with time. High convective area is located over the Indu-Malaysian region during March and low convective activity occurs over the Sri Lanka area and the lowest convective activity is located over India (OLR > 300 Wm^{2}) during normal year. However, during the El-Nino year, convective activity of this area gradually decreases until March. In February the lowest convective area

(OLR > 270 Wm^{-2}) extends towards the equator and Sri Lanka is found with very low convective activity (OLR>270 Wm^{-2}) during El-Nino year. This indicates that the large-scale circulation systems such as Hadley and/or East-West (Walker) circulations are weakening in those areas. Area north of the equator is subjected to low convective activity, meanwhile Southern Hemisphere indicated high convective activity from January to March during El-Nino year.

By April, the low convective activity (OLR > 290 Wm^{-2}) located over the central part of India and over the Arabian sea. Over Sri Lanka the convective activity is low (OLR > 250 Wm^{-2}) during El-Nino year. In fact, high convective activity (OLR < 240 Wm^{-2}) area covers the central Indian Ocean in the Southern Hemisphere. Sumathipala (1989) has shown that the OLR value is at the minimum around 155E, (OLR < 200 Wm^{-2}) but the values over Malaysia-Indian Ocean area are slightly higher. The area of OLR maximum (low convective activity) over India extends south-westward over to the equatorial south Arabian sea indicating subsidence and suppressed convection during El-Nino year. Starting from May the high convective area moves towards the Northern Hemisphere (NH) during the El-Nino year and the central Indian Ocean shows suppressed convection. OLR increases (low convection) from May to August over the Indian subcontinent and maritime continent area during El-Nino year. Therefore, it can be concluded that, low convective activity over this areas may lead to low precipitation during El-Nino year.

During September Fig.11 of the normal year an elongated narrow band of low convective activity forms in the north-south direction in the western side of the Indian Ocean which is absent during El-Nino years. However during El-Nino year this area shows high convective activity.

During El-Nino year SST of this area is greater than the normal year. and this warm sea area may contribute to enhance the convective activity. During November Fig.12 highly convective area moved towards the equator from the Northeast side of the Indian Ocean and by December the Arabian sea is marked with low convective activity (OLR>240 Wm^{-2}) during El-Nino year.

1.g. Longitudinal and Latitudinal movements of OLR field over the Indian Ocean during the time period of 1974-1990

During the time period of 74 - 90 there are two types of OLR fluctuations prominent in the equatorial Indian Ocean. The period of 1974 - 1982 exhibit low convective (dry type) activity while the other period 1983 - 1990 shows high convective (wet type) activity).

During this two decades there were three El-Nino events. It is noted that for the two El-Nino events in 1976/1977 and 1982/1983 there were strong low convective activity in the study region as compared to the 1986/1987 El-Nino event. Murakami (1989) have mentioned that the birth place of 82/83 El-Nino event was the western Indian Ocean. His findings are in agreement with the findings of Yasunari (1987). Further, this eastward moving wave of ENSO mode with a speed of about 0.3 m/s was estimated by Murakami and Sumathipala (1989), Murakami (1989). At this speed the signal takes about 5 years to travel around the world.

1.g.1 Time Latitudes/ Longitudes section for the region X (30^o N-30^o S , 70^o E-90^o E)

In the year 1975 during the 75/76 La-Nina event, there was a clear northward movement of high OLR field in the Southern Indian Ocean. However, during the same time period Sri Lankan area was covered with a low OLR (high convective activity) movement for several months. During La-Nina year the monsoon trough over central India is very active (Krisnamurthi, 1971) and is associated with strong Walker and weak Hadley circulations and linked with the weak subtropical jet stream of the Northern Hemisphere. Gutzler and Harrison (1987), Suppiah (1989) have observed that strong (weak) upper easterlies and strong (weak) low level westerlies during La-Nina (El-Nino) years. And thus give below (above) normal rainfall in the second intermonsoon season. During the 76/77 El-Nino most of the study domain experienced stationary type of low convective activity (dry) and Sri Lanka had experienced dry weather. The time-Longitudinal sections revealed that during the period from 1974 to 1980 most of the study regions succumb to eastward moving low convective activity.

1.g.2 Time Latitudes /Longitudes section for the region Y (30° N-30° S , 90 E-110° E)

Longitudinal and Latitudinal movement of OLR field of the region Y was different from the region X. During the period from 1974 to 1980 most of the equatorial regions have experienced dry type of movement (low convective activity). During this period there was a signal that moved northward from the Southern Hemisphere (SH) to Northern Hemisphere (NH) in the 3rd quarter of 1975 (indicated by blue line) Fig.13. However, there was a (low convective activity) Latitudinal movement in the study area during 1976 to 1978 and this dry type signals (low convective activity) moved north-eastward from the SH towards the NH. During the 76/77 El-Nino event, there is a high low convective activity movement north-eastward in the towards the equatorial region (indicated in red line). During the period from 1980 to 1990 most of the areas over the study region showed high convective activity of latitudinal movements. A dry type (low convective activity) anomaly signal moved north-eastward from the SH towards NH at the end of year 1981 prior to the 82/83 El-Nino event Fig.14, (indicated by red line). After the 82/83 El-Nino event, a wet type (high convective activity) movement had occurred in the study area from mid 1983 to 1986.

There was a high convective activity signal in the 3rd quarter of 1982, which started and propagated from the SH with a northeastward direction towards the Northern Hemisphere Fig.I5, (indicated by green line). During 86/87 El-Nino event, a clear north-eastward movement of low convective activity was found in the Southern Indian Ocean from south west of the domain Fig.16. During the period from 1988 to 1990 there was a low convective activity signal in the northwest of the Indian Ocean of the NH and propagated towards the equatorial region Fig.16, (indicated by blue line). Based on the findings it could be concluded that these anomaly signals appear prior to the development of El-Nino in the Pacific Ocean. It can be suggested that the origin of the El-Nino phenomenon may lie in the Indian Ocean itself.

During the time period of 1974 to 1990 the fluctuation of OLR field in the region 1 (20N-0, 50E-110E) is different from the region 2 (0-20S, 50E-110E). The period of 1974 to 1979 exhibit low convective activity movements in the region 2 rather than the region 1 (from 1974 to 1979) strongest low convective activity within the region was observed in contrast to the period from 1980 to 1990. Further in of 1976 there was a severe dry type OLR fluctuation observed in the region 1 as compared with the region 2. From the end of 1975 to 1977 low convective activity in the region 1 gradually moved in a southeastward direction. During this time period convective activity is very low in the Sri Lanka area.

From 1979 the OLR activity decreases in the region 1 till the end of 1981. In 1982 the region 1 shows high convective activity as compared with the region 2. During the period of 1983 to 1987 region 1 exhibited dry type movement of OLR while the region 2 shows wet type movement except the year 1987. In 1988, the OLR activity decreased in the region 2 rather than the region 1. Further; convective activity enhanced in region 2 during the time period of 1989 to 1990 with compared to region

2. Sea Surface Temperature (SST) in the study domain

2.a Annual Standard Deviation of SST in the study domain.

Standard deviation of the SST for the region was calculated on monthly basis and these values were used to plot spatial pattern in the region. From the plotting it was seen that a region of high variation of SST is located near the Arabian sea region, around the Bay of Bengal and Northeast China Sea.

It was also evident that a sudden increasing trend of SST towards the East Coast of African after the month of May, up to August.

2.b Variation of Sea Surface Temperature (SST) in the Indian Ocean during El-Nino year

In order to study the different between El-Nino and normal year means Composite Maps were produced. Composite Maps for El-Nino indicates that, the high SST (> 29° C) field lies just over the equator and spread over a large area in the Indian Ocean Fig.17.

During a normal year the high SST occurred in the maritime continent and the neighboring area Fig.18. The area, which has SST greater than 29 °C, is located in the Western Pacific Ocean (around 130° E).

During an El-Nino year high and low SST areas are observed with relative to normal year. In the east coast of Africa, Bay of Bengal and the China sea SST values are high. On the other hand, low SST areas are located in the northern part of the Mediterranean sea and Gulf of Arabia. Shukla and Misra (1977) in their study has shown high wind speed related to the low SST over the Arabian sea. This strong wind may cause increase evaporation and up-welling, which lead to colder SST over the Arabian sea. These results tend to suggest that the stronger winds cool the surface, and that colder SST persists for more than a month and contribute to reduction in the monsoon rainfall for the following month. Liang et al., (1995) commented that cooler ocean temperatures and increased land sea thermal difference create greater intensity monsoon circulation. On the other hand, such cool temperatures may lead to decrease evaporation, which may lead to a reduction in available moisture and a weaker monsoon.

During the El-Nino year, high SST areas emerged from the eastern part of Indian Ocean. In the month of February, central Indian Ocean is much warmer than the normal year. Joseph et al., (1994) showed that, the Indian Ocean warm much faster than the western Pacific Ocean between February and April.

In April the warm area (SST > 29 °C) is well developed on both side of the Equator. Afterwards it is gradually moved towards the Northern Hemisphere. It is observed that beginning in March the tropical Indian Ocean, north of equator warms very rapidly and a large area attains SST > 29 °C. This area may be called the Indian Ocean warm pool.

During the month of June, warm pool encompasses around the Indian subcontinent and adjacent South China Sea with SST in excess of 29.5 °C. After the month of June these areas gradually decrease towards the north west side up to December. Therefore it can be argued that in the later half of May or early June before the monsoon sets, the warmest area should lie in the Indian Ocean north of equator. Shukla and Fennessy (1994) have observed that annual cycle of the SST in the Indian Ocean is crucially important in establishing the monsoon circulation and rainfall. Model simulations also confirm that the Arabian Sea SST influences subsequent monsoon rainfall on time scales less than a month.

After the month of July up to September warm pool gradually moved towards the northeast Indian Ocean. The warm pool begins to spread in October and move towards the northeast Indian Ocean till December. In the Bay of Bengal warm pool exists during the month of September and October. Therefore, it may be concluded that these areas highly affect the North East Monsoon over Sri Lanka.

2.c. Longitudinal and Latitudinal movements of SST in the Indian Ocean during the period of 1971 – 1990.

In the time Longitudinal sections of SST in the region YY there was a clear indication of a positive anomaly signal starting to propagate near the 58° E

Fig.19 (indicated by red arrow line) in the year 1971, prior to the 72/73 El – Nino event. This type of signal could propagate towards the Pacific Ocean to produce an El–Nino signals. Tourre et al., (1995) have shown that the Indian Ocean, has an El-Nino of its own. Also cold type anomaly started to propagate from the Western Indian Ocean in 1971 and reached the Western Pacific Ocean in the year of 1972.

During the 72/73 El-Nino there was a strong positive anomaly movement of SST in the study area Fig.19. Usually El–Nino phenomena is identified near South American coast in Eastern Pacific Ocean when SST rise above normal during the month of December. However, this movement (indicated by blue arrow) appeared in the month of January 1972 in the Western Indian Ocean from the 41° E Longitudes

In 75/76 La-Nina event, a negative anomaly movement in the Western Indian Ocean toward the Pacific Ocean was observed Fig.20 (Indicated by white line).

During the 76/77 El-Nino event, the positive anomaly movement has started from the Western Indian Ocean towards the eastern side of the study domain.

There is an appearance of a positive anomaly movement prior to the 82/83 El-Nino event. It was clearly observed that, this signal started to propagate from the Eastern Indian Ocean in the mid 1980 and it reached the Western Pacific Ocean in the end of 1981. This signal could be the El-Nino signal propagating towards the Pacific Ocean from the Indian Ocean Fig.21.

In the 82/83 El-Nino event, it was clearly seen that there was a strong positive anomaly movement propagating from Western side towards the Eastern side of the Indian Ocean. Fig.22. However, in the mid 1983 there was also a strong positive anomaly movement in the study area. In general, El-Nino event takes its peak strength during the preceding year (in December of 1982), but this area showed strong positive anomaly movement in the middle of the year 1983 (red arrow line). Tourre et al., (1995) discovered an El-Nino pattern in the Indian Ocean that is lock with that in the Pacific Ocean but dynamic process within each oceans appear to be different. During the same periods the Pacific warm pool migrate eastward to create the El-Nino in 82-83 and 86-87, while El-Nino also formed in the Indian Ocean.

There was a positive anomaly movement in the year 1987 in the study domain in 86/87 El-Nino event. It was clearly seen that negative type movement propagated from the Western Indian Ocean towards the Eastern side during the 88/89 La-Nina event. However, this negative (cold) type movement diminished in the Eastern side of the Indian Ocean around 98^0 E longitudes.

Considering twenty years time period, it is clearly observed that during the seventies (1971 –1976), negative (cold) anomaly movement was present in the study area. From the 1977 up to 1990 it was noted that most of the years showed positive (warm) type SST fluctuation except during the years 1978, 1984 and 1985. The Indian Ocean SST is dominated by a strong positive trend, warming greater than 0.018 ^{0}C degrees per year, in the Equatorial Eastern Indian Ocean. It was found that most of the warming in the Indian Ocean has occurred after 1976 and the warming is weak throughout the Indian Ocean prior to 1976. Mcphaden et al., (1998) have shown that using the TOGA (Tropical Ocean-Global Atmosphere) system, average SSTs in the tropical Pacific were unusually high during the 1980s and 1990, at the same time there was a trend for warmer global surface air temperature. The tropical Pacific SSTs were warmer because of a greater intensity, frequency, and duration of warm ENSO events.

2.d Variation of rainfall of Sri Lanka in relation to SST in the Indian Ocean

Influence of SST in the Indian Ocean with the SWM and NEM rainfall were investigated. Highest positive correlations were found in the region R1, RX2 and R4 during SWM period (Table-5). Using the lag correlation it was observed that there is a positive correlation with rainfall when SST lags of 1, 2, and 3 months. When SST leads 3 months before the SWM rain onset over the monsoon domain, the regions R1, R4 and RX2 showed negative correlation with rainfall in wet zone of Sri Lanka. This implies that these regions are cooler before the SWM season and contribute to enhance the rainfall during SWM period. During the NEM period highest positive correlations were found in the region R2 and RC with the rainfall in Dry zone (Table-6). Region R2 showed positive correlation when SST leads 1 and 2 months respectively. It can be concluded that for these regions SST may be used to predict the SWM and NEM rainfall of Sri Lanka .

It is noted that during March of a during La-Nina year positive rainfall anomalies were observed in southwest and southeast part of the Sri Lanka.

Beginning of the summer monsoon season during El-Nino year, Somalian sea area showed high positive correlation while most of the areas in western Indian Ocean showed (weak) positive correlation. Negative correlation was also observed in the central Indian Ocean but weak when compared to the La-Nina year. It is observed that during June of a La-Nina year below normal rainfall prevailed in Sri Lanka. Therefore, it can be concluded that SST play an important role in the Sri Lankan rainfall.

3. Variation of Rainfalls of Sri Lanka in relation on to El-Nino and La-Nino phenomenon

3.a. El-Nino Year

When normalized rainfall index was plotted a few striking features can be identified. January through April the index shows negative values over most part of the island Fig.23, Highest negative values are found in the northern and northwestern part of the island during January and February Fig.24. In January, most dry areas are located in the northwestern part and have index value around -30. Further, it gradually increases up to -10 towards the central part of the country (Fig.25). Strong dry condition prevail all over the island (during February) Fig.23. February rainfall index is less than -60 in the north-central part of the country and this indicate that Northeast Monsoon (NEM) rainfall is less during El-Nino year. This condition extends into the First Inter Monsoon (FIM) by recording negative index values over most of the island.

Beginning of the FIM, central part of the island and southwestern slope of the hill country and central part of the dry zone received slightly above normal rainfall and the rest of the country received below-normal rainfall Fig.24. During March and April only a marginal increase is found in a small region in the central part of the country. This indicates that large-scale circulation associated with El-Nino influence rainfall over the island.

In a normal year Southwest Monsoon (SWM) onset fall on second week of May and heavy rainfall is observed in the southwestern part of the island. However according to this analysis high percentage of above normal rainfall is found in the central and northern part of the country during El-Nino year. During June Fig.26, extensive rainfall received over most part of the Dry Zone. Suppiah (1984) shows a sudden increase in June rainfall during El-Nino year is associated with the fluctuation of the Inter Tropical Convergence Zone (ITCZ) in the Sri Lankan area. Furthermore, these findings agreed well with Sumathipala and Murakami (1986).

In this study it can be seen that abnormal rainfall occurred during June in the northeast part of the country during the El-Nino year. It may be concluded that during the El-Nino condition large scale atmospheric circulation alters the normal condition of the atmosphere over the Sri Lanka. Composite picture for El-Nino show, that during June above normal rainfall region shift eastward and below normal rain is received over a large area in the central part of the country. This has expanded during July and shift eastward by August. However there is a significant different between rainfall distribution in the month of June and August Fig.27 & Fig.27. These two months shows opposite character in relation to rainfall. The northwestern part of the country received more rainfall during June while during the month of August enhanced rainfall is found in the southwestern part. It is interesting to note that this character is compatible with active and break phase conditions noted by Sumathipala and Murakami (1986). During September, area of negative anomaly of rainfall is found in the southwestern part of the country. But Second Inter-Monsoon (SIM) as a whole produces excess rain over the island. This period even extend to December during El-Nino year.

Fluctuation of the rainfall during the five El-Nino events (76/77, 82/83, 86/87, 91/92, 92/93) shows substantial anomalies between the twelve rainfall stations in Wet Zone and Dry Zone. Variation of rainfall in Colombo during this five events show two different type of fluctuations between 76/77, 92/93 and 82/83, 86/87, 91/92. When 76/77 and 92/93 considered, 76/77 received substantial rainfall as compared with the normal rainfall pattern in the first three months and low rainfall was experienced at the end of the year. In 92/93 more rain was received during the first nine months and less rain occurred during rest of the year. In the events in 82/83, 86/87, 91/92 entirely negative anomalies (less rainfall) occurred. Composite patterns of wind components at Colombo for La-Nina and El-Nino studied by Suppiah (1989), have shown that during the early stage of an El-Nino event, Inter Tropical Convergence Zone (ITCZ) is usually weak and lies far south of its mean position and gives little or no rainfall to Sri Lanka.

However, during these two years (76/77, 92/93) Colombo received considerable rainfall as compared with the other years. Examining the rainfall figures between the 77/78, 92/93 El-Nino events, it is evident that 92/93 receive more rain in the first nine months of the year. Even though, the other events (82/83,86/87,91/92) received a little amount of rain and strong dry condition occurred in 86/87 El-Nino event.

When up country rainfall stations (Kandy, Nuwara -Eliya and Diyatalawa) are considered it can be seen that the rainfall variation of each station followed the same pattern during five El-Nino events. In contrast, they faced drought condition during the 82/83, 86/87, and 91/92 except the 76/77, 92/93 events. In the hill country, Nuwara-Eliya faced the driest condition in 82/83 as compared with the 86/87, 91/92 El-Nino events.

Wet Zone rainfall stations (Colombo and Galle) receive less rain during the 82/83, 86/87, 91/92 El-Nino event. High rainfall figures can be seen in the month of May and October in the 76/77 El-Nino events for the Wet Zone and several stations in the Dry Zone. Ratnapura indicates powerful negative rainfall departure from the normal in 77/78 and the 86/87 El-Nino events and 86/87 was the most strongly affected year. It is clearly evident from the plotting that the first three months of the El-Nino year received more rain as compared with the normal year rainfall for all stations. Colombo and Galle are the most affected in the El-Nino years of 82/83, 86/87, 91/92 as compared with the other stations in the Wet Zone.

Analyzing the time series plotting for the Dry Zone rainfall stations (Trincomalee, Batticaloa, Badulla, Anuradhapura, Maha-Ilupppallama and Kurunagala), it is clearly evident that several stations (Kurunagala, Maha-Iluppalama and Batticaloa) received significant rainfall during the month of May to July in the El-Nino years as compared with the normal year the Trincomalee, Batticaloa and Anuradhapura rainfall stations show in-phase rainfall fluctuations in the 76/77, 82/83, 86/87 El-Nino events. During an El-Nino year the first nine months shows positive rainfall figures as compared with normal year rainfall. On the other hand, the strong dry situation has taken place in the 86/87 El-Nino event more than the other four El-Nino events. As it can be observed, the other stations (Badulla and Maha-Iluppallama) show similar rainfall pattern throughout all the El-Nino events. Kurunagala is the most affected area during the 86/87 and 92/93 El-Nino events. When the five El-Nino events are considered together, the rainfall of the first half of the El-Nino year shows substantial increase in rainfall at Maha–Iliuppallama. However, during the first half of the 86/87 El-Nino event most of the stations received plenty of rainfall except in the Kurunagala.

3.b La-Nina year.

Beginning of the first inter-monsoon period during La-Nina year most of the area received above normal rainfall except the eastern part of the country. A clear difference was observed in April in a La-Nina year when compared with the El-Nino year.

During La-Nina year it was observed that at the onset of the SWM southern and northeastern slope of the hill country received below normal rainfall. While most of the country faced dry condition a marginal increase of index by less than 10 is found in a small region in the central part of the country.

During the latter part of the SWM above normal rainfall was received throughout the country. However, in July below-normal rainfall was experienced in eastern part of the country. Above normal rainfall was received in the hill country and northern to eastern part of the country. The first month of the second inter-monsoon period received above normal rainfall and by the end of October the whole country showed negative rainfall anomaly. During NEM period below normal rainfall anomaly was observed throughout the country except the southeastern during November and December. Southern part and hill country received below normal rainfall towards the end of the NEM period.

4. Rainfall fluctuation in Wet zone and Dry zone during the time period of 1900 to 1996.

From the spectral analysis for the Wet Zone and Dry Zone rainfall stations exhibit different types of fluctuations within the period from 1900 – 1996. In the Wet Zone rainfall stations, six-month oscillation is prominent. However, Nuwaraeliya, Ratnapura, and Diyatalawa show equal strength of 6 and 12-month oscillation.

In the Dry Zone 12-month oscillation is prominent. Only Kurunagala exhibits 6-month oscillation prominently. However, it was also seen that the 6 month and 3 month oscillation is in an equal strength. Individual rainfall stations in the Dry Zone, show 3, 6 and 12-month oscillations.

For the other rainfall stations in the hill country, Kandy, Nuwara-Eliya and Badulla there are three major dominant fluctuations of 3, 6, and 12-month oscillations and the other rainfall fluctuation modes are weak. In Kandy, mainly 6-month oscillation is prominent and 119-month oscillation was also significant.

In the Dry Zone when individual rainfall stations were considered, it was observed that the amplitude of the 12-month fluctuation is prominent. In Batticaloa, rainfall fluctuation of 6, 12 months oscillation is significant, while it was also seen that the 25, 39, 105, 144, and 195-month oscillation amplitudes are in significant level when compared with the 3-month fluctuation. As regards the Dry Zone rainfall fluctuations 12-month oscillation is prominent and in the Wet Zone rainfall fluctuation, 6-month oscillation is dominant rather than the 12-month oscillation.

VI. CONCLUSIONS

The area over the Southern tip of the Indian subcontinent shows high variations of OLR, during the month of November. During NEM period, higher fluctuation of OLR field is prominent in the Sri Lankan area (15N-5S, 77.5E-82.5E). These areas have a changing convective activity throughout the year.

It is very important to place emphasis on the OLR variation in the Southern and the Northern Hemispheres during El-Nino years. Over Asia during January to March the two hemispheres indicate opposite behavior. North of the equator indicate dry condition (low convective activity) meanwhile South of the equator shows wet condition (high convective activity). In an El-Nino year convective activity decreases over the Indian sub-continent and maritime continent from May to August. Low convective activity (high OLR), may lead to low precipitation in the above-mentioned area during El-Nino year.

During September of a normal year there was an elongated narrow band of low convective activity in the north south direction in the western Indian Ocean (40 E-52.5E), which is absent during an El-Nino year. Further, an anomalous convective activity associated with the El-Nino warming of the tropical south Indian Ocean may influence the monsoon activity over the region. Therefore it is worth paying attention to this area to trace the behavior of OLR field during an El-Nino year.

During El-Nino years there are noticeable changes in the OLR fields in the study domain. However, all El-Nino years are not similar and then different El-Nino events can influence climate of Sri Lanka in different ways.

OLR anomaly in time series plots of several regions indicates strong peaks during the El-Nino years in 76/77, 82/83 and 86/87. Based on these facts it could be concluded that the Indian Ocean has certain connections with the El-Nino phenomenon. The origin of the El-Nino related phenomenon is not exactly identified, however, it may lie somewhere in the Indian Ocean itself. There was a gradual decreasing trend of OLR in the region AS (15N-25N / 55E-75E) before the onset of the El-Nino.

Correlation between OLR of the sub regions in the Indian Ocean and Sri Lankan rainfall for the SWM and NEM period is significant. During SWM period highest correlation were found for the regions A, B and D with a one month lag. For the SWM period, monthly rainfall is highly correlated with the regions in the Eastern Indian Ocean indicating regional scale vertical circulation in sub scale It could be concluded that the OLR activity in the western and southwest of Sri Lanka have significant correlations with the rainfall.

Throughout the NEM period OLR is the regions in the western Indian Ocean showed highly significant correlations with rainfall of Sri Lanka. Highest negative correlation was found in the region K and H with a one months lag.

There are dissimilarities of the OLR fluctuations in the region 1 (20° N-0, 50° E-110° E) and region 2 (0° - 20° S, 50° E-110° E). The period of 1974 to 1979 showed strong dry condition type OLR movement in the region 1 and, in 1976 the Sri Lanka region experienced the driest condition. During this time period whole region was affected by drought conditions because of the low convective activity.

During the time period (1974-1990) there were three El-Nino events and the two El-Nino events of 1976/1977, and 1982/1983 strongly affected the study domain when compared to the 1986/1987 El-Nino event.

An area with high variation of SST was located near the western side of the study domain and spreading towards the southeast direction in the Southern Hemisphere. There was a high variation of SST near Australian sea. As far as the northern part of the study area is concerned, SST variation is also high in the Arabian Gulf area and in the Arabian sea region. The Arabian sea area has a clear relationship with rainfall of Sri Lanka.

Correlation between SST of the sub regions in the Indian Ocean and Sri Lanka rainfall for the SWM and NEM period have a significant relationship. There is a positive correlation with rainfall when SST leads 1, 2 and 3 months. During the NEM period highest positive correlations were found in the regions R2 and RC with the rainfall in Dry zone. SST in the Indian Ocean indicates a significant relationship with the rainfall in Sri Lanka during El-Nino/La-Nina year.

Unlike in a normal year, during an El-Nino year a large area of the Indian Ocean experiences SST greater than 29 ^{0}C. The high SST areas begin to emerge in the Indian Ocean in the month of February. From the month of March up to June, north of the equator of the Indian Ocean warms very rapidly which is significantly different from that of a normal year. Composite maps of the SST field in the Indian Ocean during El-Nino and normal years reveal that, during an El-Nino year Indian Ocean plays a significant role in the weather and climate of the Asian region.

Clear eastward movement of positive / negative SST anomaly signals were evident in the western Indian Ocean towards the western Pacific Ocean prior to development of El-Nino/ La-Nina in the Eastern Pacific Ocean.

Considering twenty years time period, it is clearly evident that during seventies (1971 -1976), negative (cold) anomaly movement was present in the study area. From 1977 up to 1990 most of the years in the study area there were positive (warm) SST fluctuation except during the years 1978, 1984 and 1985. The Indian Ocean SST was dominated by a strong positive increasing trend, with the strongest warming, greater than 0.018 ^{0}C per year, in the equatorial Eastern Indian Ocean. Most of the warming in the Indian Ocean occurred after 1976 and the warming is weak throughout the Indian Ocean prior to 1976. There is an increase of SST by 0.33 ^{0}C in the ocean surrounding Sri Lanka after the year 1978.

There is a decreasing trend in SST in the Indian Ocean after occurrence of an El-Nino event.. This decreasing trend in SST persists for roughly 25 to 35 months. There was a roughly 5-year fluctuation in SST in several regions in the study domain.

There was a strong 60-month (5 year) fluctuation of SST in central Indian Ocean and increasing trend in SST nearly 0.4 °C after year 1975. Generally it has been accepted that the maximum five-year cycle is associated with warm episodes of El-Nino phenomenon. It is clear that when El-Nino takes place the SST values are high for the relevant year. In this region 60-month oscillation of SST is greater than that of 6-month fluctuation associated with the annual cycle.

The behaviour in SST field in the Indian Ocean during 76/77 El-Nino event is different from the other El-Nino events. In 76/77 El-Nino period Indian Ocean showed above normal SST for most of the months. The two La-Nina events in 75/76 and 88/89 showed opposite types of SST fluctuation patterns in the Indian Ocean. In most of the months in 75/76 event whole Indian Ocean showed positive SST anomaly. The behaviour of SST fluctuation in the Indian Ocean during 75/76 La-Nina event is somewhat similar to the 76/77 El-Nino event. This clearly shows that Indian Ocean is not fluctuating the Pacific Ocean in all El-Nino oceans. During the 20 year time period when El-Nino events occurred Indian Ocean showed negative SST anomaly in most of the months and negative areas located in the Western Arabian Sea. However, further investigation into Indian Ocean SST behaviour will lead to better understanding of climatic change scenarios in Sri Lanka and it may be applicable to other tropical regions. Finally, it could be stated that SST plays a major role in the prediction of weather and climate of Sri Lanka.

Rainfall

There were different types of rainfall fluctuations in the Wet Zone and Dry Zone rainfall stations from 1900 to 1996. Six-month oscillation was prominent in the Wet Zone and 12-month oscillation is prominent in Dry Zone. There were several low frequency oscillations except for the major oscillation in several rainfall stations. In Ratnapura 20, 30, 100, 163 and 240 months oscillations were dominant and it carried very high amplitude values.

Most of the rainfall stations throughout the country showed 17 - 19 month oscillations. Remarkable waves in the spectral band appeared at 25-

28 months, which has a strong peak, indicating that there is a Quasi-Biennial oscillation in Sri Lanka. Periodic cycles of 36-48 months and also dominates in all rainfall stations of the country.

There was a decreasing trend in the Dry Zone rainfall during the period of 1918 to 1952 and sharp Decreasing trend occurred during 1963-1978 decreasing trend in rainfall from 1928 to 1961(33 years) was slightly larger. in the Wet Zone when compared with the decreasing trend of Dry Zone rainfall. After the year 1961 it was seen that there was a decreasing trend in rainfall in the Wet Zone up to 1985.

The rainfall Index January through April showed negative value over most parts of the island. As a whole, the First Inter Monsoon (FIM) recorded less rainfall than normal during El-Nino year. However, during the Second Inter Monsoon (SIM), rainfall was above normal. During an El-Nino year there was a reduction in rainfall during NEM period and most of the northern and eastern parts of the island was affected. However, high percentage of above normal rainfall was experienced in the month of August in the central and western parts of the country during El-Nino year. During the NEM period only December received above normal rainfall throughout the country in El-Nino year.

The two months, which start the two monsoons, namely May and December recorded above normal rainfall during El-Nino year. However the regions of the country where rainfall is received are unusual. During May central and northern part receives more rain. During December south-western part receives more rain.

Rainfall fluctuations in the Wet Zone and Dry Zone showed differences through out the five El-Nino events. During the El-Nino, positive rainfall anomalies occurred for several stations in contrast to the normal year.

During the first Inter-Monsoon period, during La-Nina year most of the area received above normal rainfall except the eastern part of the country. During La-Nina year it was found that the beginning of the SWM southern and northeastern slope of the hill country received below normal rainfall. However, in June this situation is agravated and most of the country faced dry condition .

The first month of the second inter-monsoon period received above normal rainfall during La-Nina year but in October the whole country experienced below normal rainfall. During NEM period negative rainfall anomaly was observed throughout the country except the southeastern part.

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Wet zone

Rainfall in Wet Zone		
Spectral Line No	**Oscillation in Month**	**Power Density 10^{-4}**
1	17	2.68
2	28	2.86
3	30	1.9
4	39	2.06
5	44	2.45
6	47	1.33
7	50	1.19
8	61	0.75
9	77	0.54
10	119	1.4
11	387	1.08

Dry zone

Rainfall in Dry Zone		
Spectral Line No	**Oscillation in Month**	**Power Density 10^{-4}**
1	17	2.09
2	19	2.01
3	25	2.57
4	30	1.11
5	36	1.67
6	39	2.59
7	50	0.75
8	61	0.96
9	69	0.99
10	77	0.87
11	105	0.46
12	169	0.48
13	387	0.64

Table 1. Power Spectrum for Rainfall in Wet zone and Dry zone

Wet Zone	Rainfall	5 year cycle
Spectral Line No	Oscillation in Months	Rainfall (mm)
1	27	228
2	85	187
3	165	206
4	237	191
5	298	250
6	392	240
7	445	220
8	514	239
9	566	233
10	633	243
11	705	240
12	838	238
13	931	240
14	1012	241
15	1067	242
16	1141	248

Dry Zone	Rainfall	5 year cycle
Spectral Line No	Oscillation in Months	Rainfall (mm)
1	41	142
2	88	124
3	160	158
4	244	150
5	306	154
6	378	164
7	453	158
8	525	163
9	583	160
10	702	168
11	771	169
12	854	168
13	937	169
14	1014	166
15	1089	168
16	1158	170

Table 2. Rainfall fluctuation in Wet Zone and Dry Zone (5 term weighted running mean)

Table (3). SWM / OLR

Region	r(1)	p(%)	r(2)	p(%)	r(3)	p(%)
AS	-0.302	0.27	+0.177	0.68	-0.006	0.98
S	-0.349	0.21	+0.164	0.56	+0.194	0.49
B	-0.389	0.15	+0.055	0.85	-0.705	0.80
C	-0.082	0.77	+0.277	0.32	-0.692	0.004
D	-0.374	0.12	-0.180	0.94	+0.239	0.389

Table (3). Correlation coefficient (r) between OLR and SWM rainfall in Wet zone of Sri Lanka. The numbers in the brackets gives number of months OLR leads. p value give the percentile level of significance.

Table (4). NEM / OLR

Region	r(1)	p(%)	r(2)	p(%)	r(3)	p(%)
G	+0.050	0.860	+0.134	0.640	-0.014	0.960
K	-0.249	0.336	-0.336	0.221	-0.356	0.199
D	+0.246	0.377	-0.308	0.263	-0.031	0.910
I	-0.137	0.627	-0.258	0.358	-0.212	0.450
J	-0.206	0.462	-0.152	0.589	-0.359	0.188
F	-0.252	0.426	-0.173	0.538	-0.332	0.227
H	-0.465	0.080	-0.198	0.479	-0.126	0.656
SL	-0.288	0.297	-0.069	0.805	+0.224	0.423

Table (4). Correlation coefficient (r) between OLR and NEM rainfall in Dry zone of Sri Lanka. The numbers in the brackets gives number of months OLR leads. p value give the percentile level of significance.

Table (5). SWM / SST

Region	r(0)	p(%)	r(1)	p(%)	r(2)	p(%)	r(3)	p(%)
RX6	-0.162	26.2	+0.292	6.85	-0.253	4.3	+0.351	9.67
R4	-0.384	2.89	+0.375	0.61	+0.195	8.67	-0 167	0.385
RX2	-0.464	0.08	+0.461	0.67	-0.173	12.9	-0.471	0.76
R1	-0.491	26.3	+0.362	12.67	-0 295	0.6	-0.357	11.3

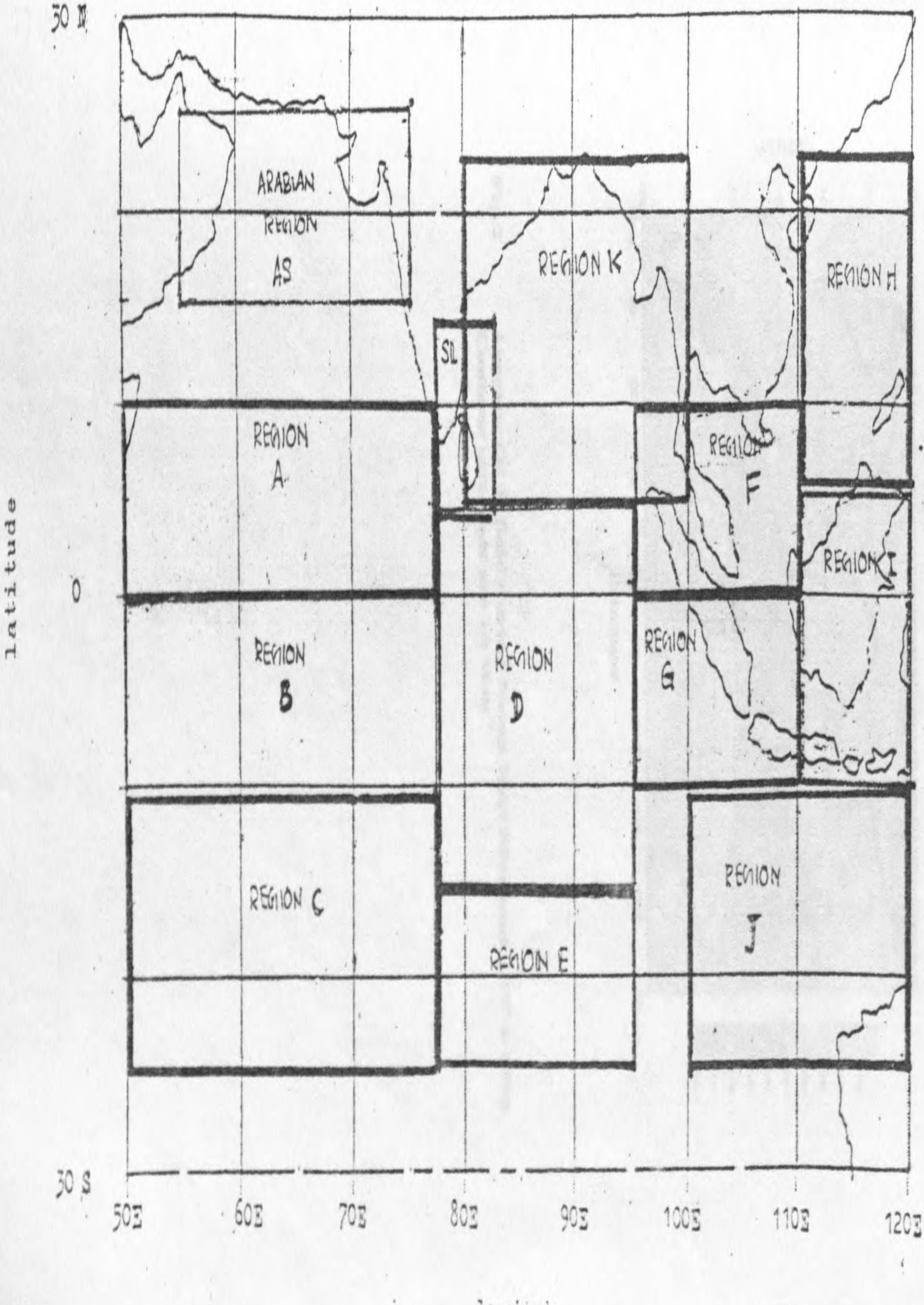
Table (5). Correlation coefficient (r) between SST and SWM rainfall in Wet zone of Sri Lanka. The numbers in the brackets gives number of months SST leads. p value give the percentile level of significance

Table (6). NEM / SST

Region	r(0)	p(%)	r(1)	p(%)	r(2)	p(%)	r(3)	p(%)
R2	+0.582	36.31	+0.487	12.67	+0.421	0.85	-0.267	18.1
C	+0.478	12.63	+0.501	0.76	+0.381	0.78	-0.351	11.96
E	+0.281	6.53	-0.321	22	+0.261	9.57	-0.422	0.63

Table (6). Correlation coefficient (r) between SST and NEM rainfall in Dry zone of Sri Lanka. The numbers in the brackets gives number of months SST leads. p value give the percentile level of significance

Fig. I Study area showing 13 sub regions



Study ... 13 sub-regions

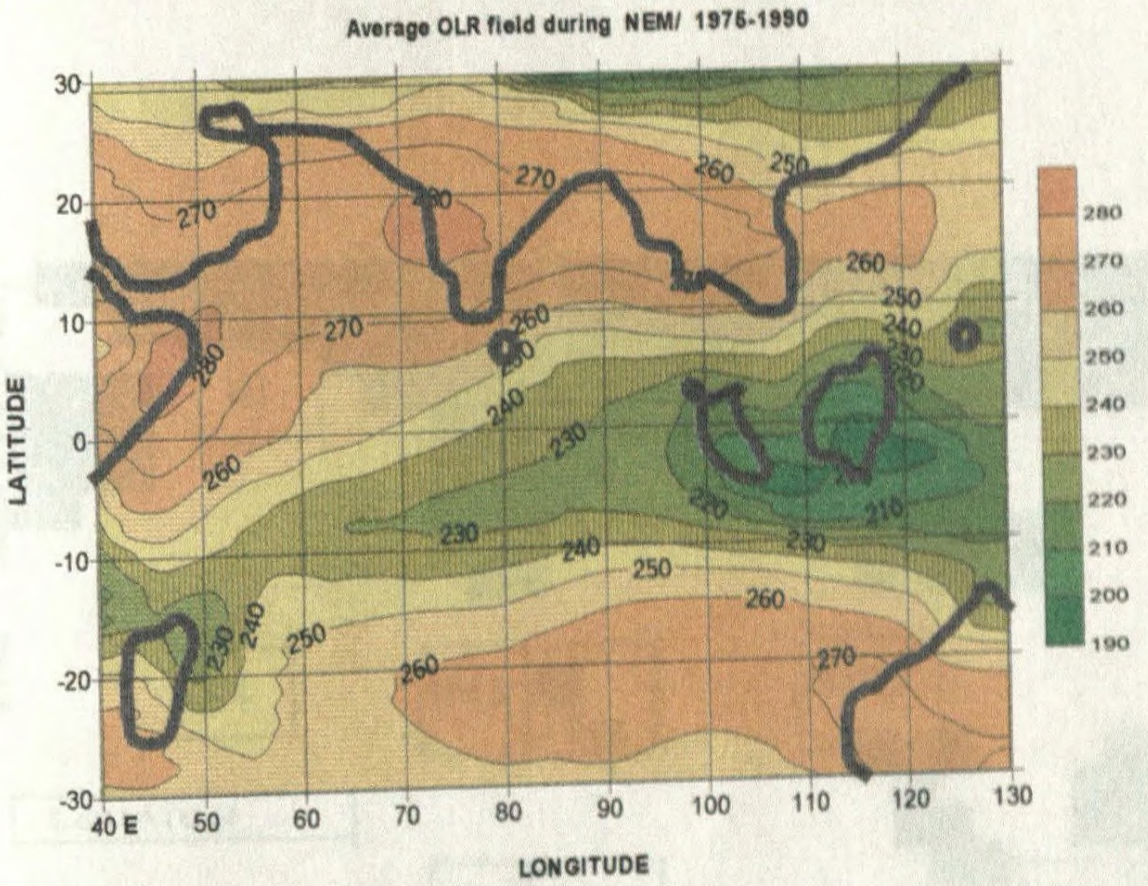


Fig.2 Average OLR field during North East Monsoon / 1974-1990
Contour intervals are 10 Wm^{-2}

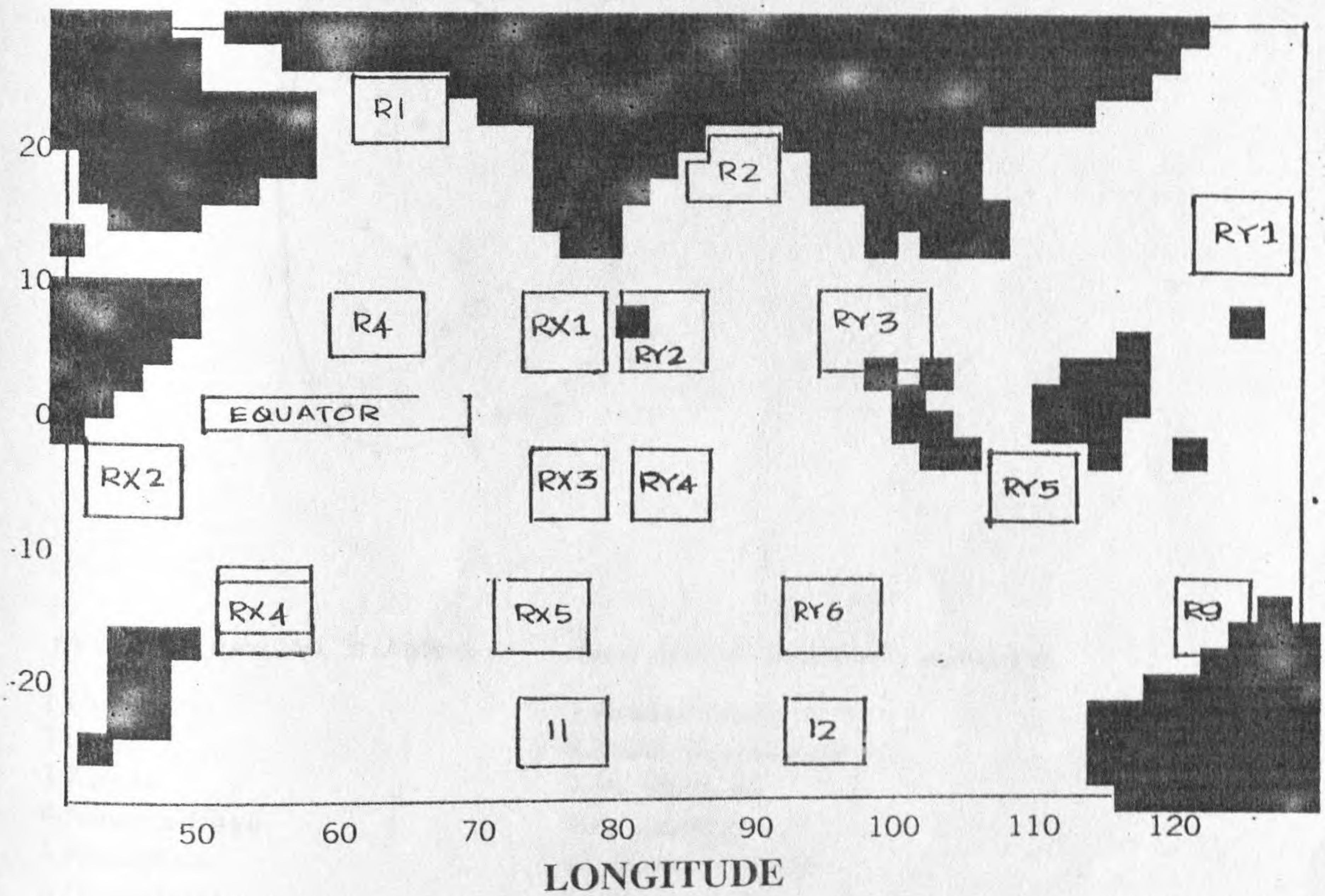
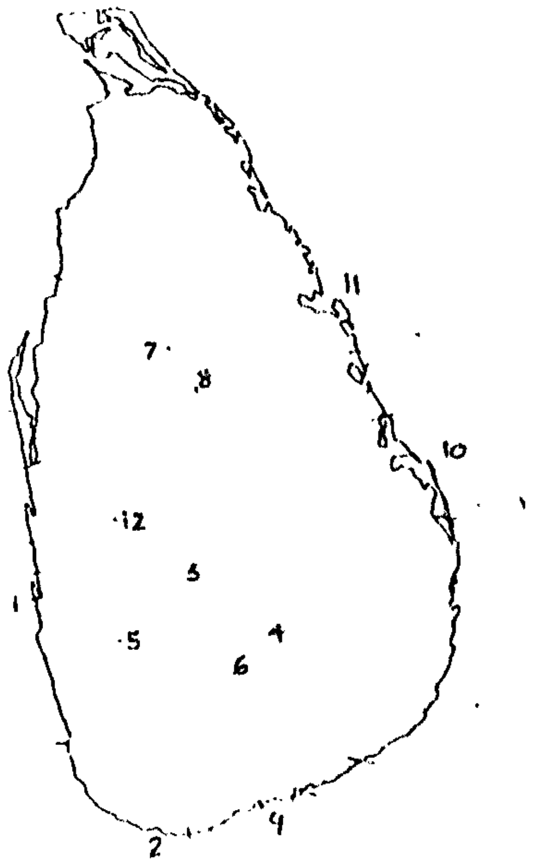


Fig.3 Selected areas in the study domain



WET ZONE RAINFALL STATIONS

1.Colombo
2.Galle
3.Kandy
4.Nuwara-Eliya
5.Ratnapura
6.Diyatalawa

DRY ZONE RAINFALL STATIONS

7.Anuradapura
8.Maha-Iluppallama
9.Hambantota
10.Batticaloa
11.Trinkomamlee
12.Kurunagala

Fig. 4 .Distribution of Major rainfall stations in the Wet zone and Dry zone.

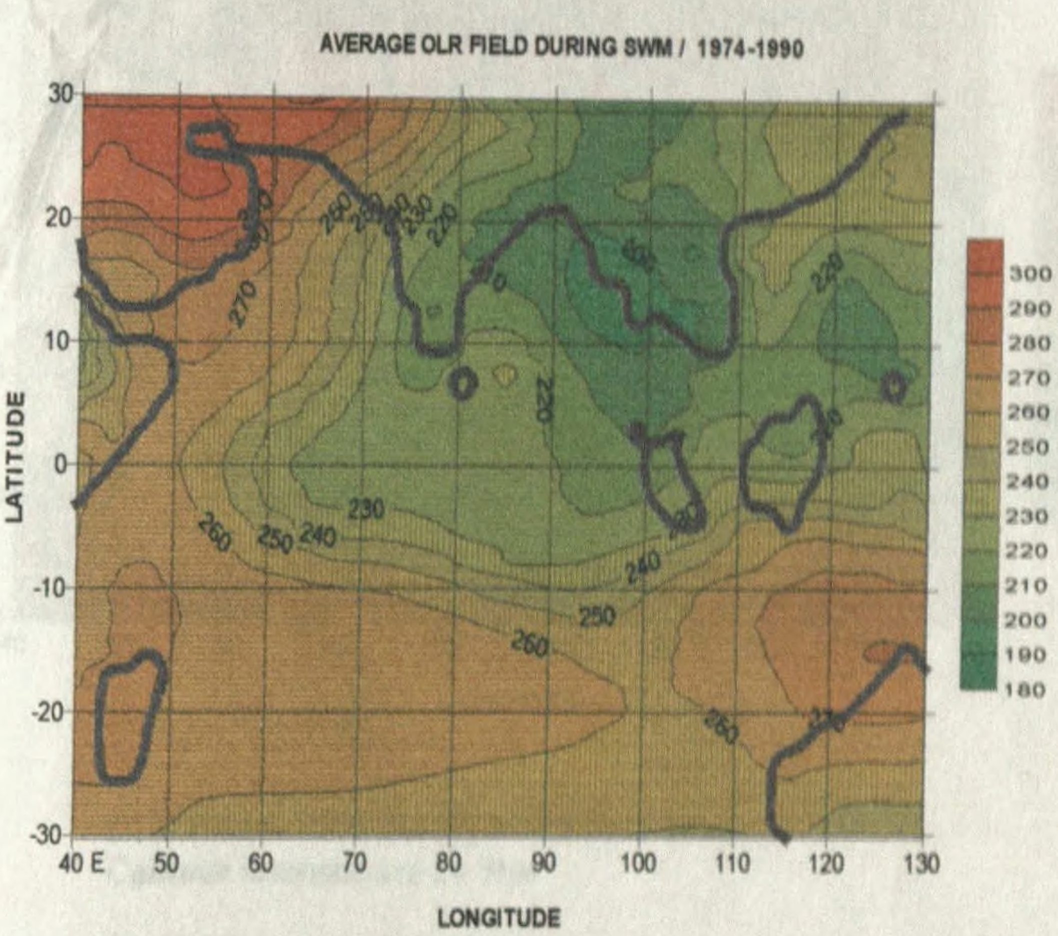


Fig.6 Average OLR field during South West Monsoon / 1974-1990
Contour intervals are 10 Wm^{-2}

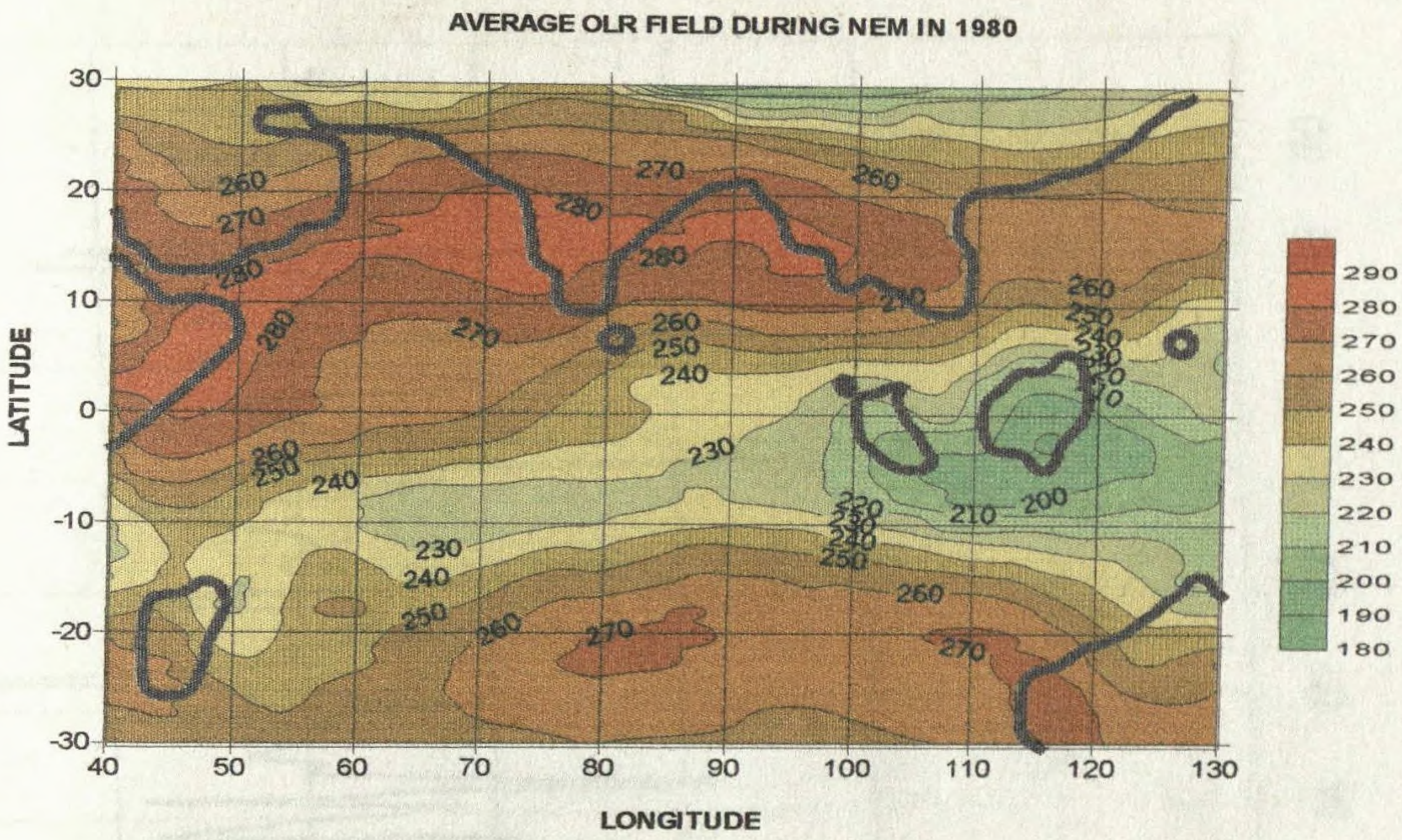


Fig..7 OLR field in 1980 during North East Monsoon. Contour intervals are 10 Wm^{-2}

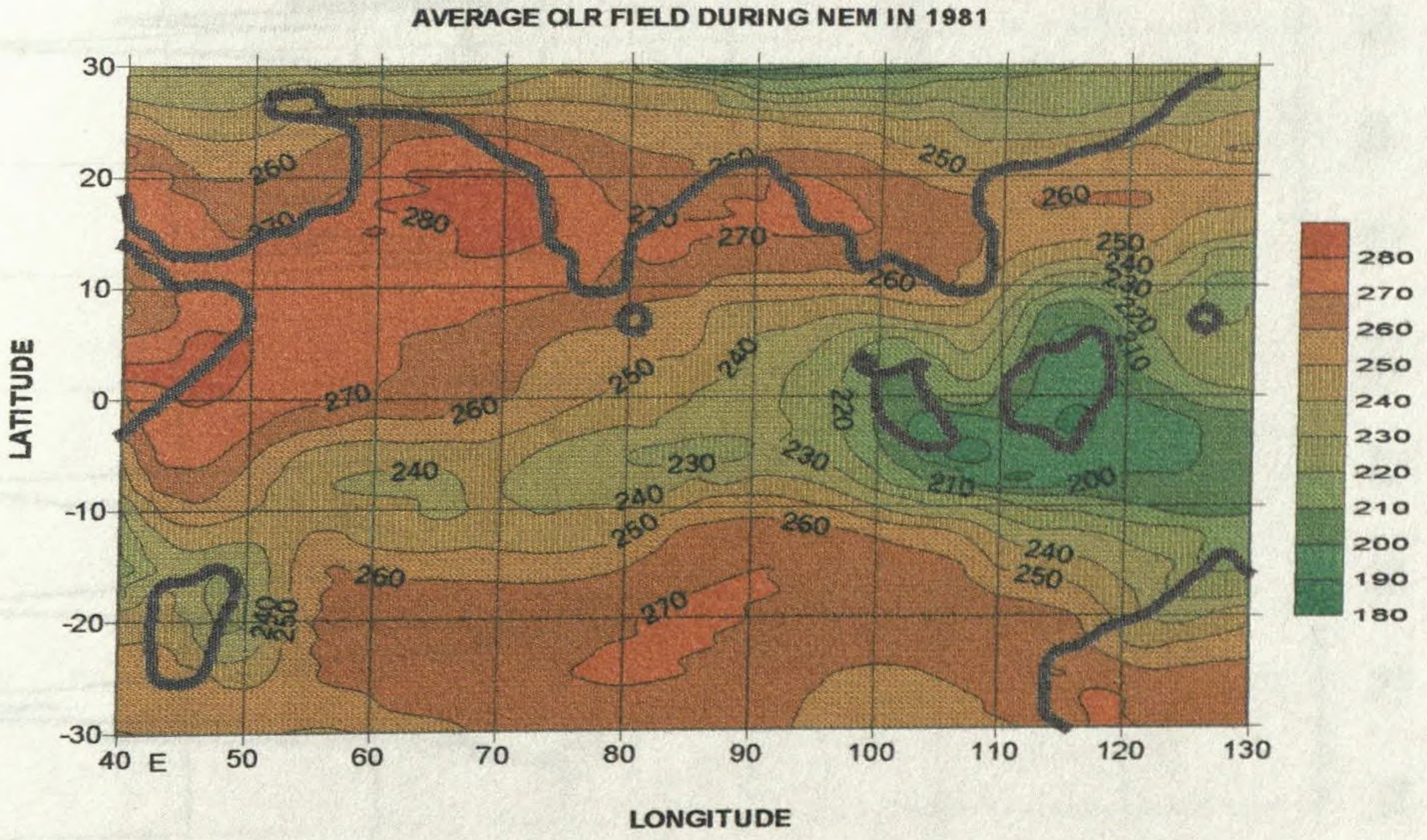


Fig..8 OLR field in 1981 during North East Monsoon. Contour intervals are 10 Wm^{-2}

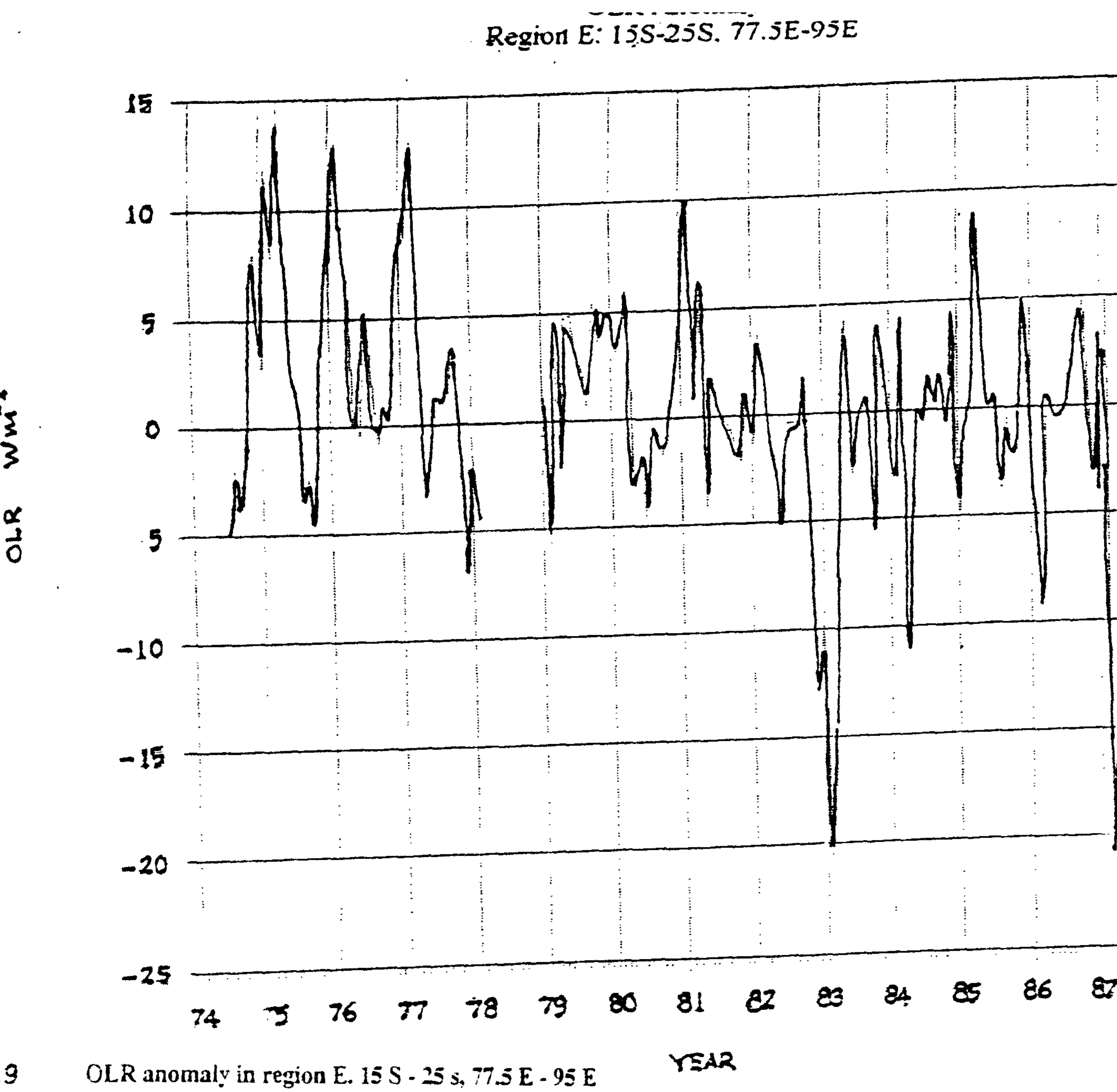


Fig.9 OLR anomaly in region E. 15 S - 25 s, 77.5 E - 95 E

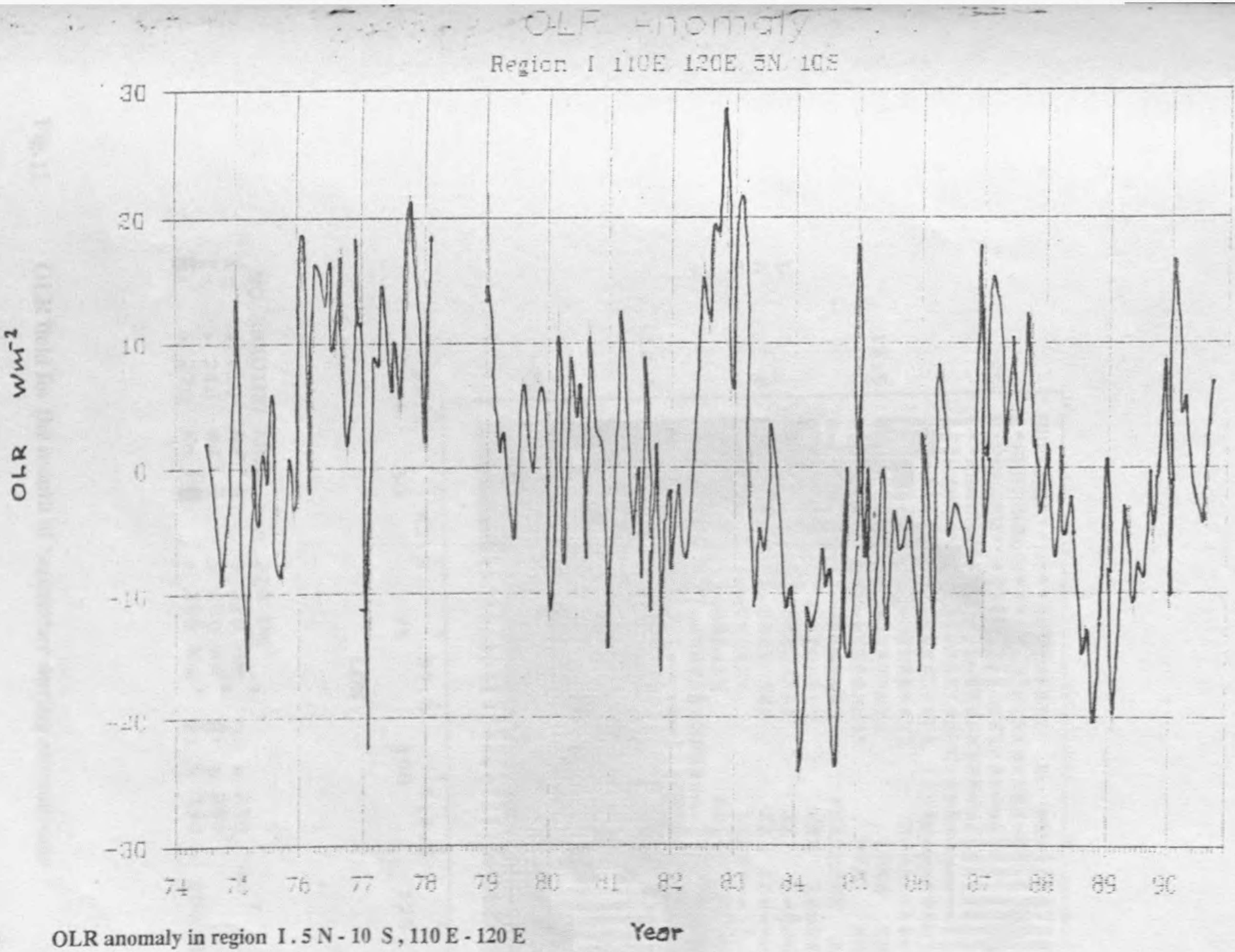


Fig.10 OLR anomaly in region I . 5 N - 10 S , 110 E - 120 E

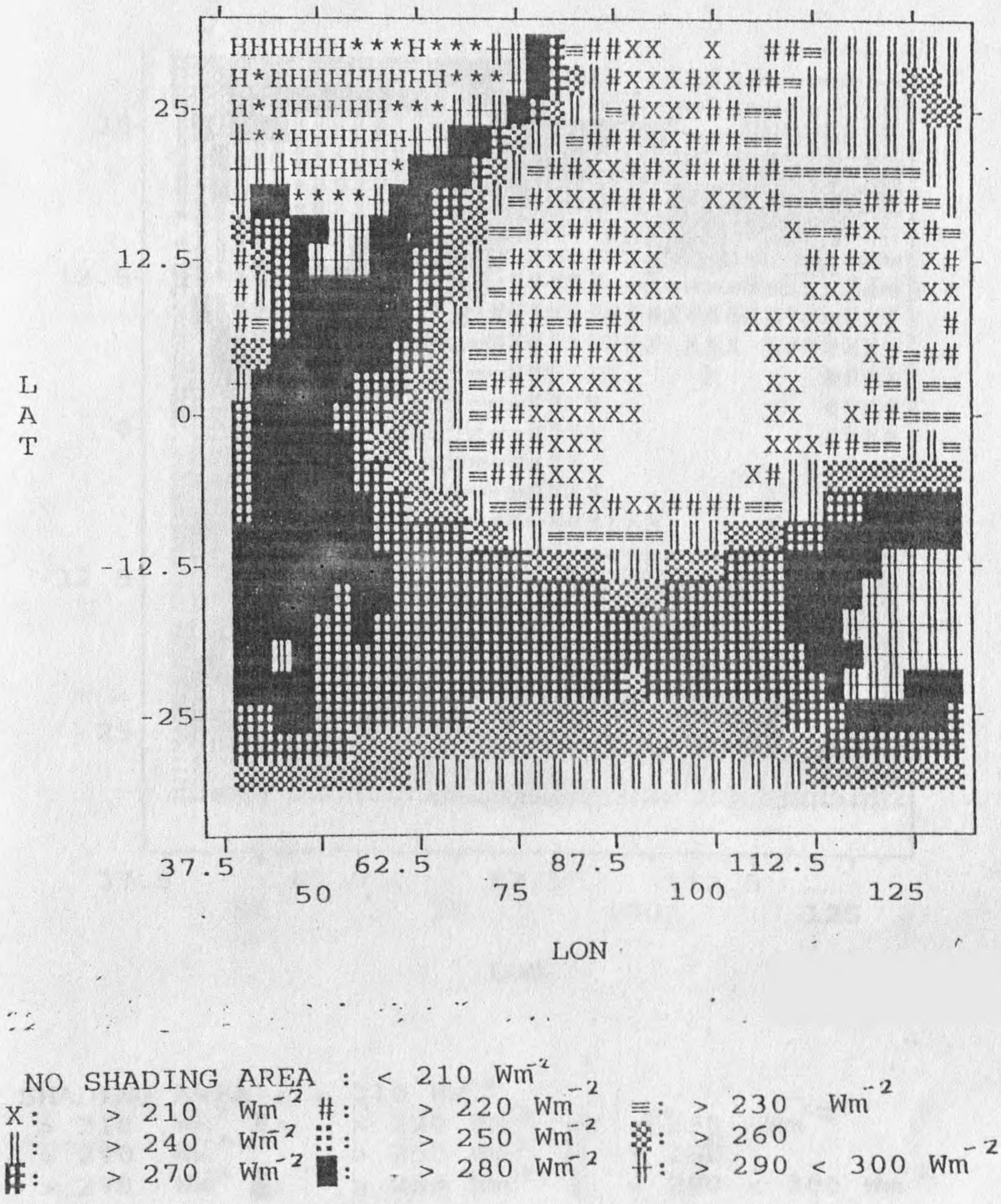


Fig. 11 OLR field for the month of September during normal year

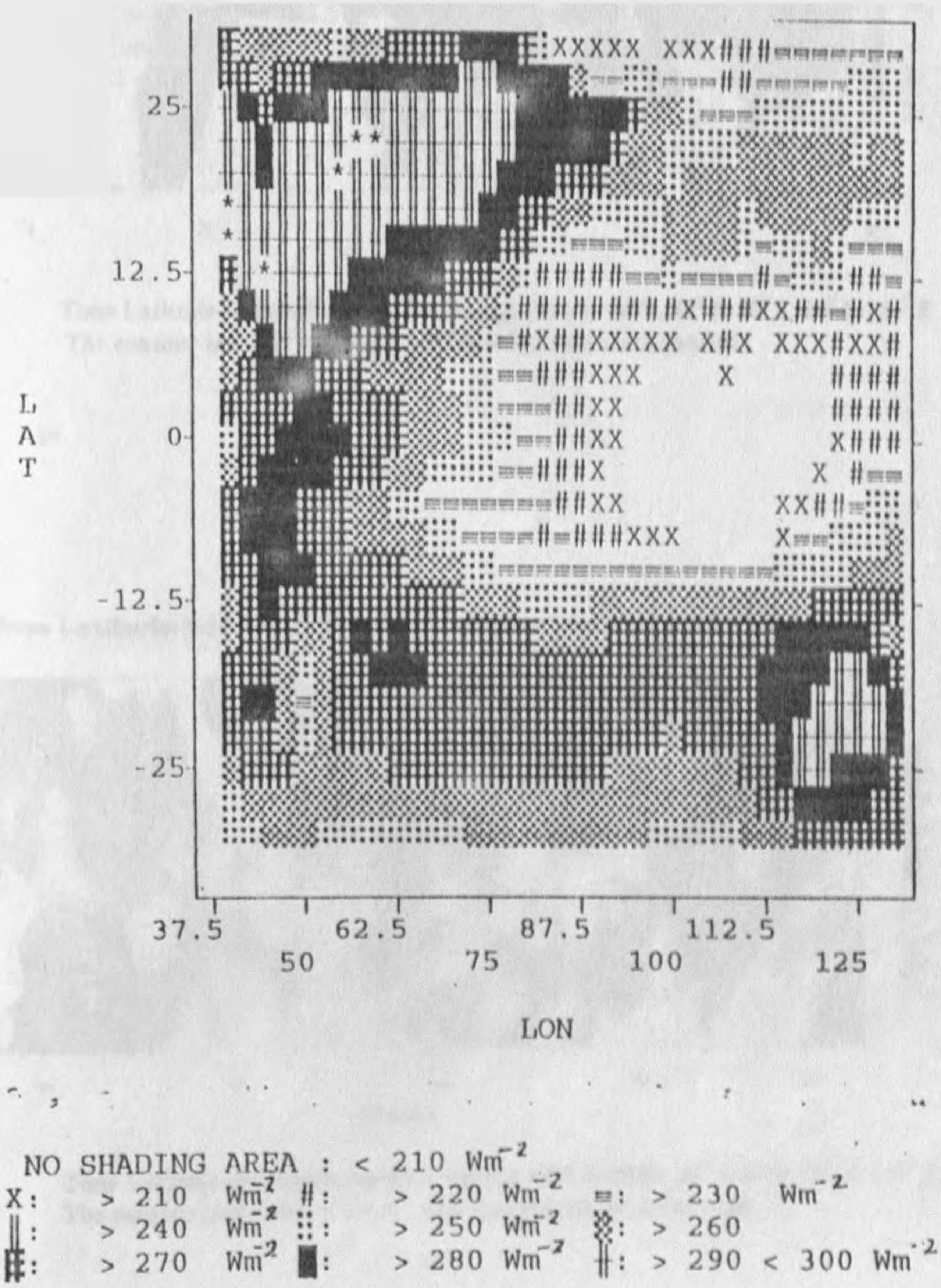


Fig.12 OLR field for the month of November during normal year

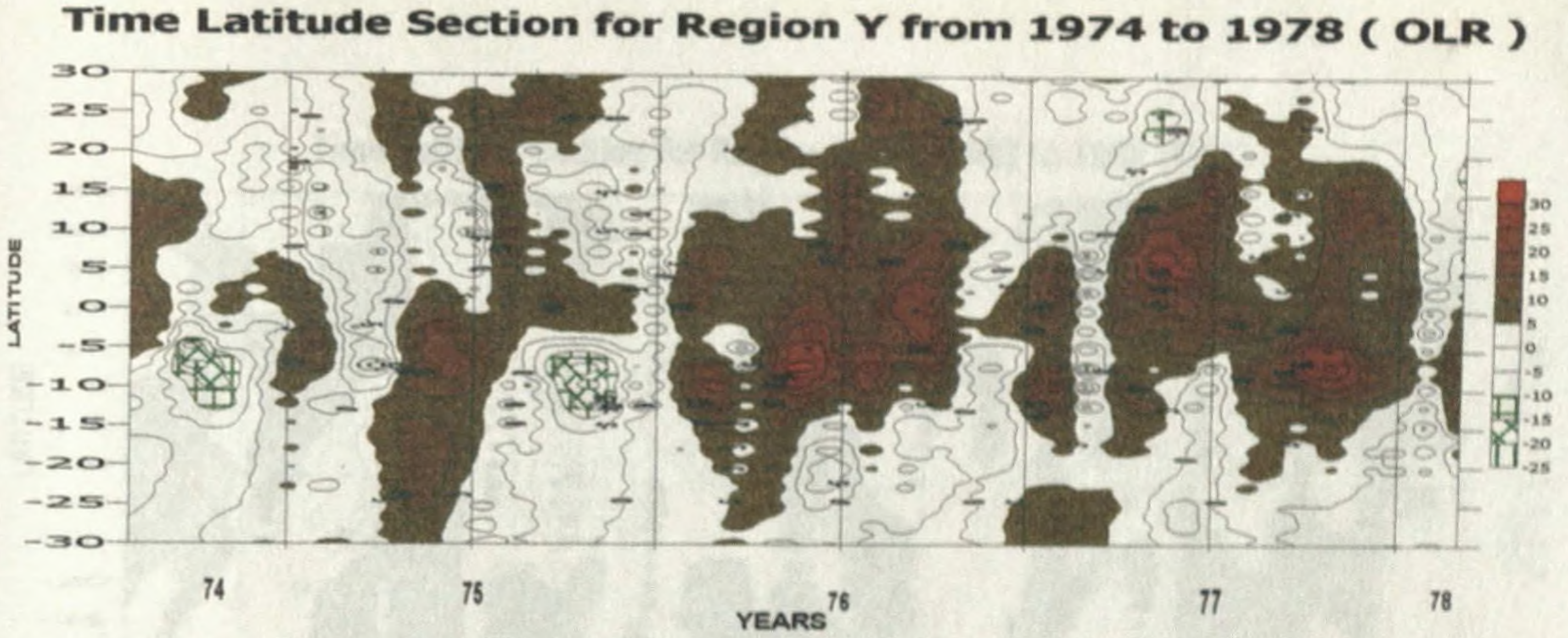


Fig.13 Time Latitude section for region Y during 1974 to 1978, 30^0 N-30^0 S, 90^0 E-110^0 E
The contour interval is 5 Wm^{-2} and positive values are shaded

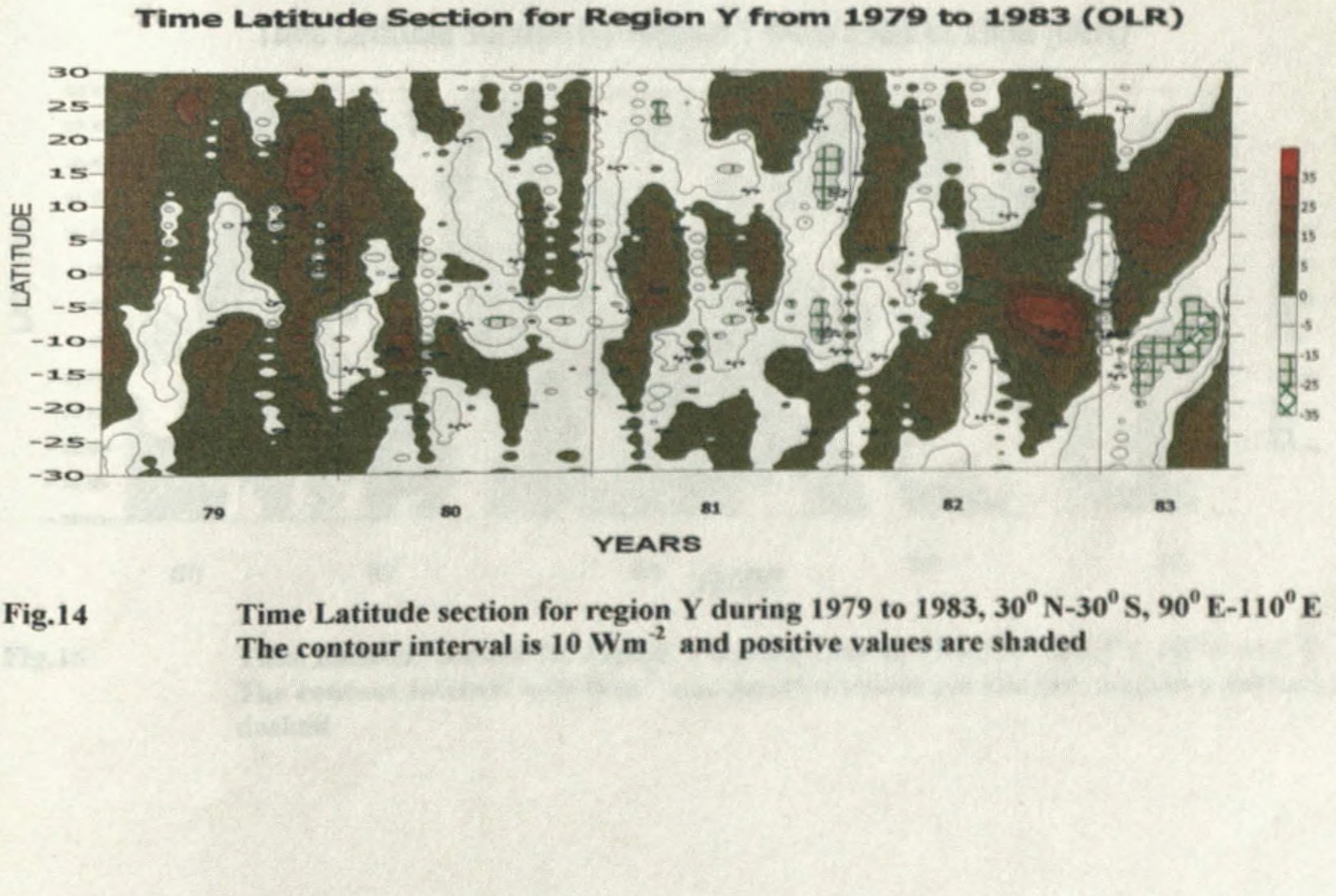


Fig.14 Time Latitude section for region Y during 1979 to 1983, 30^0 N-30^0 S, 90^0 E-110^0 E
The contour interval is 10 Wm^{-2} and positive values are shaded

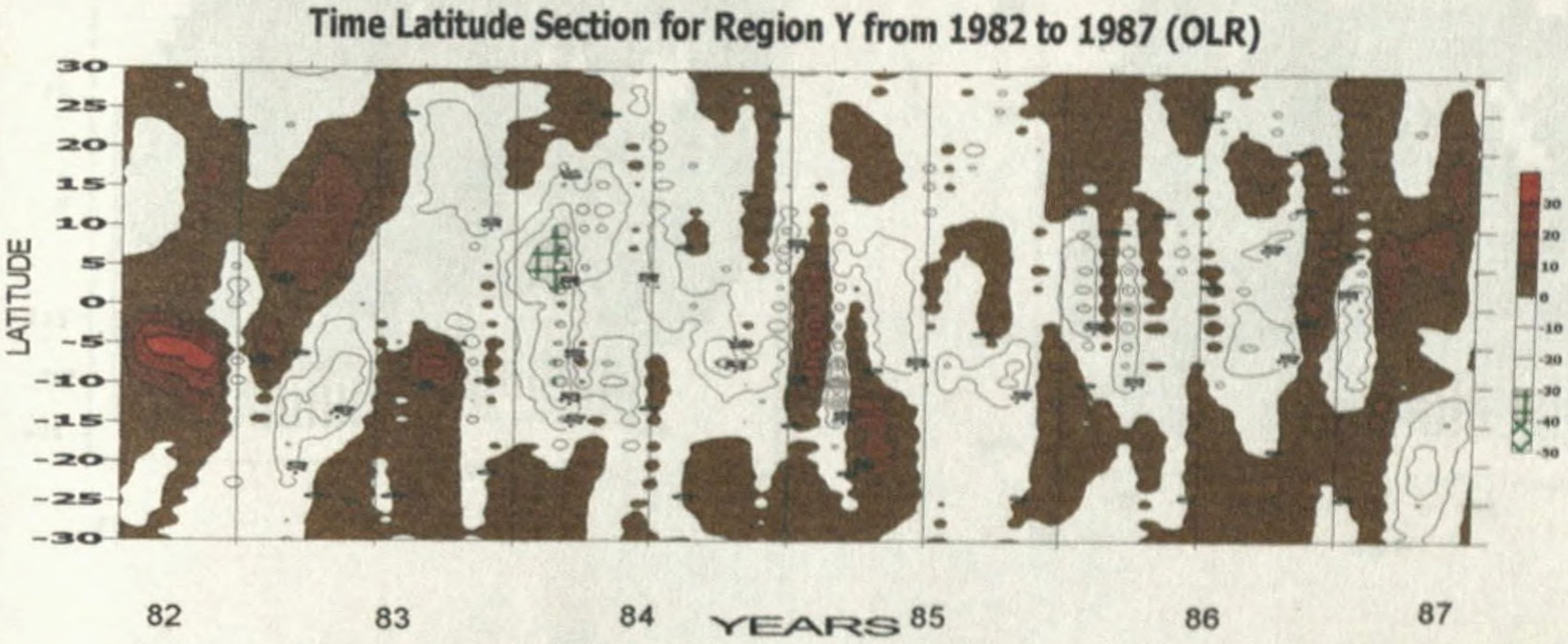


Fig.15 Time Latitude section for region Y during 1982 to 1987, 30^0 N-30^0 S, 90^0 E-110^0 E
The contour interval is 10 Wm^{-2} and positive values are shaded

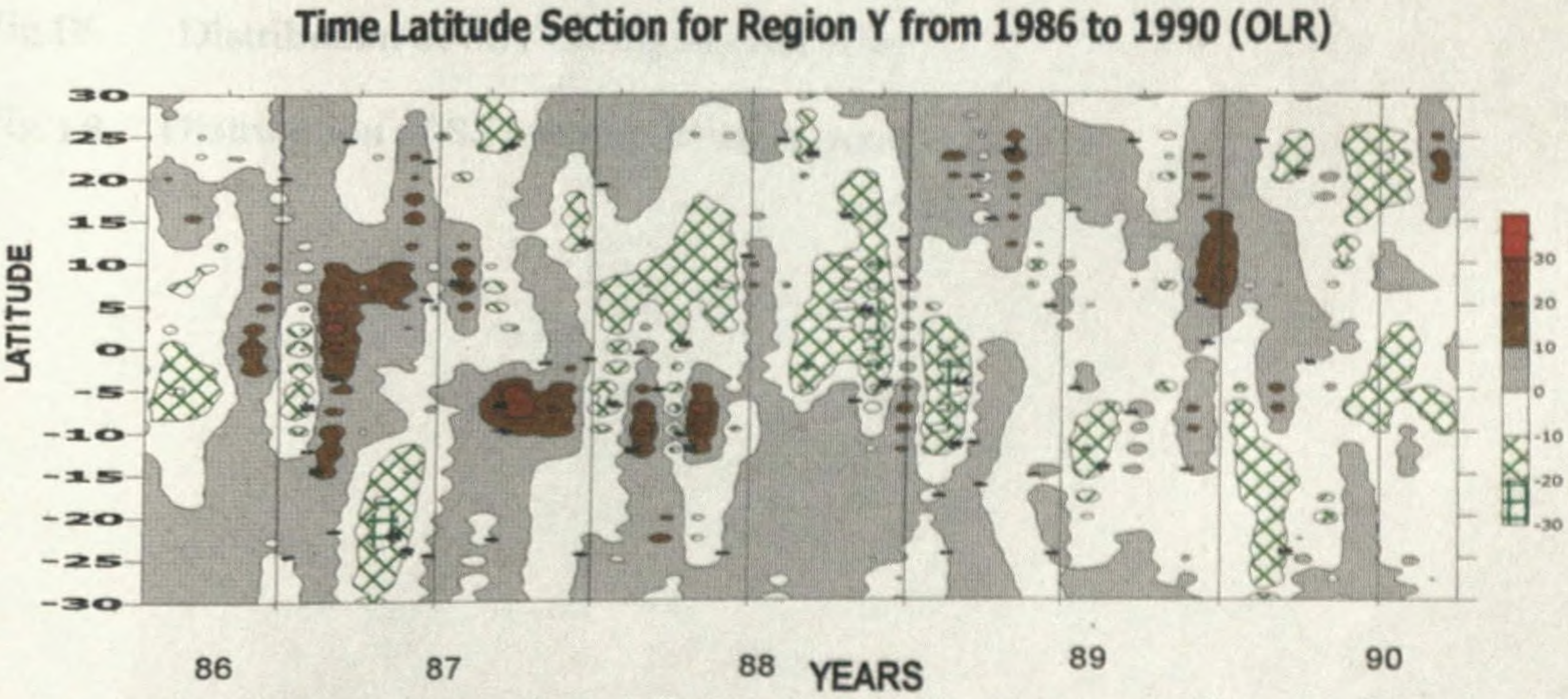


Fig.16 Time Latitude section for region Y during 1986 to 1990, 30^0 N-30^0 S, 90^0 E-110^0 E
The contour interval is10 Wm^{-2} and positive values are shaded. Negative values are dashed

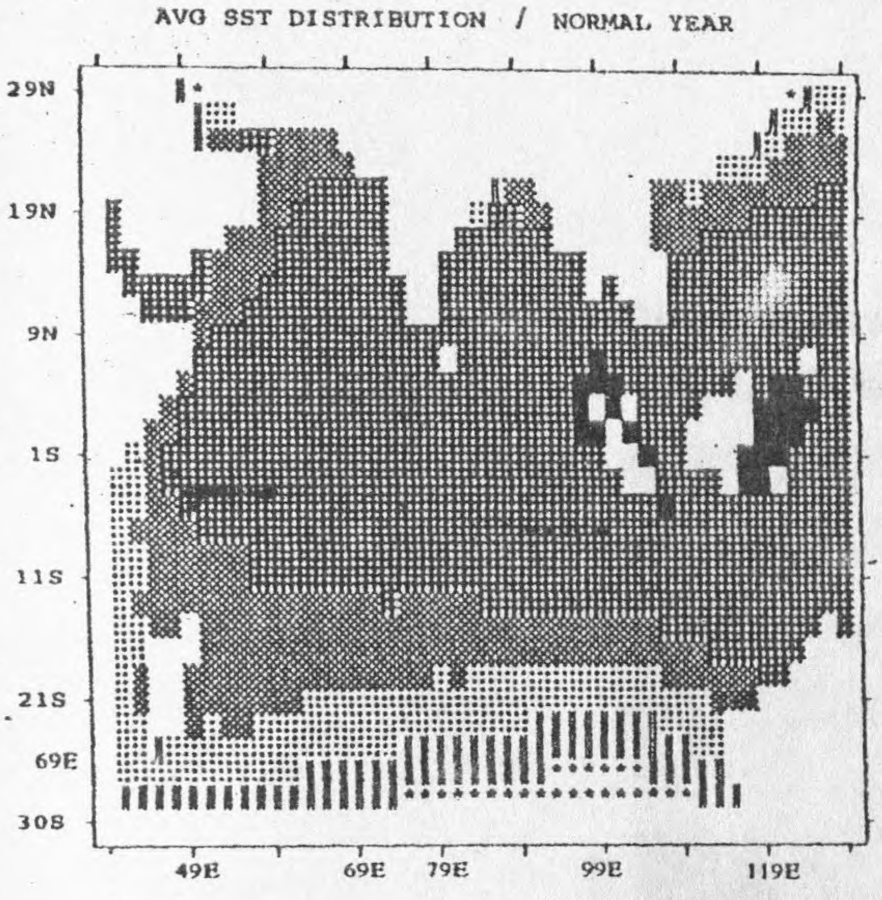


Fig - 1

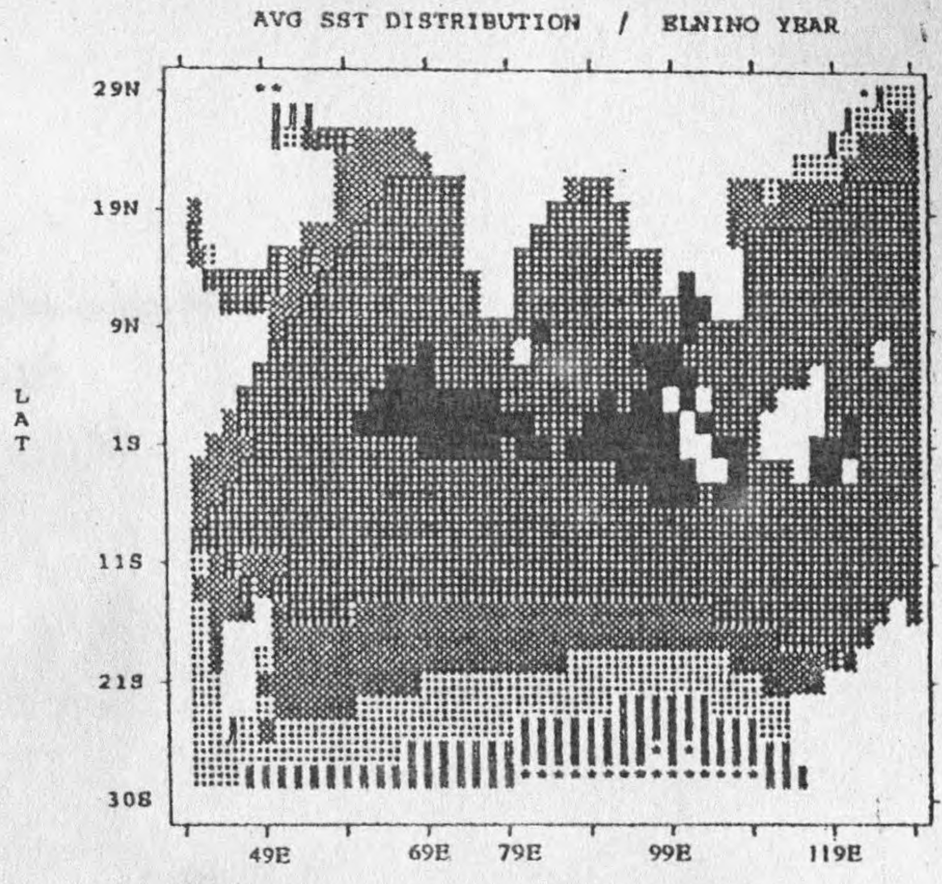


Fig - 2

Graphic codes are defined as follows

0: 12-15 C
1: 15-17 C
#: 17-19 C
*: 19-21 C
‖: 21-23 C
⠿: 23-25 C
▨: 25-27 C
▦: 27-29 C
█: 29-31 C

Fig.17 Distribution of SST during normal year.

Fig.18 Distribution of SST during El-Nino year.

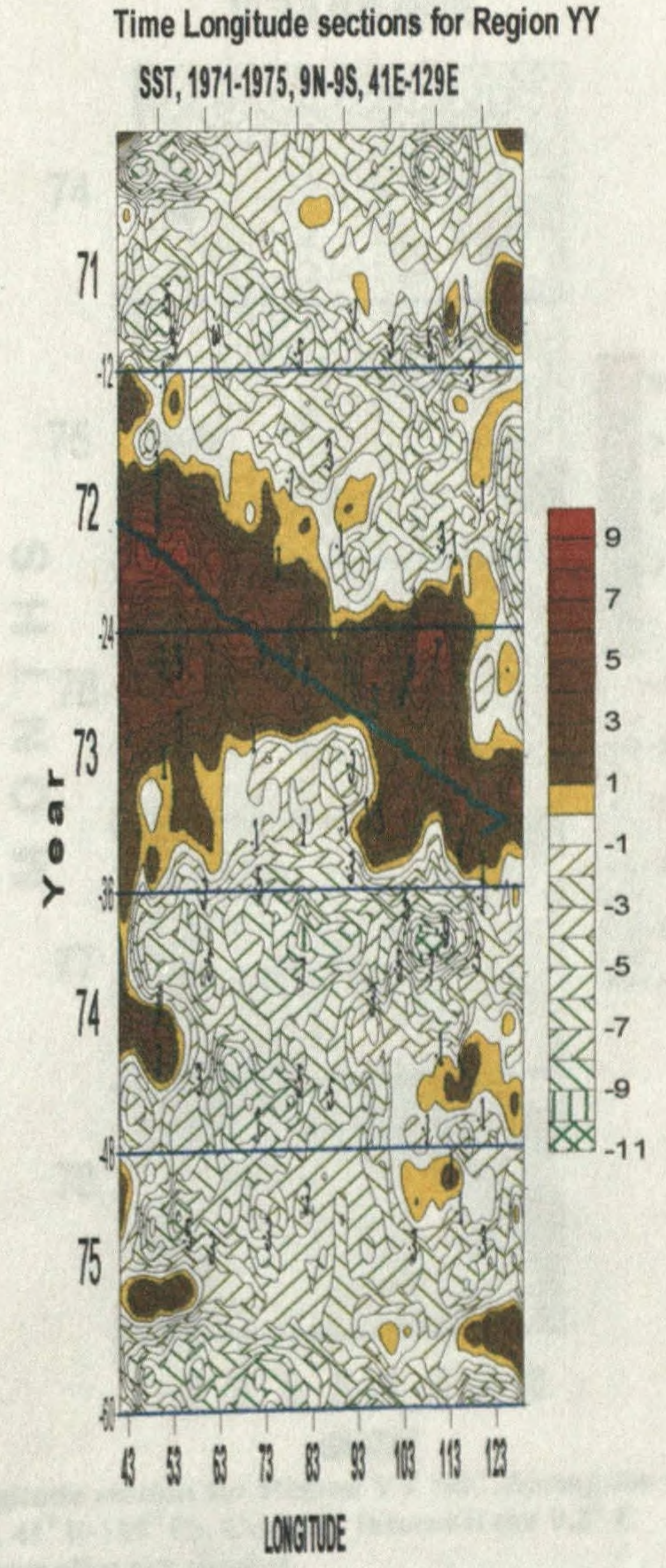


Fig.19 Time Longitude section for **Region YY SST during the time period** (1971-1975) **(9^0 N-9^0 S , 41^0 E-129^0 E), Contour intervals are 0.2^0 C,** Positive anomalies are shaded

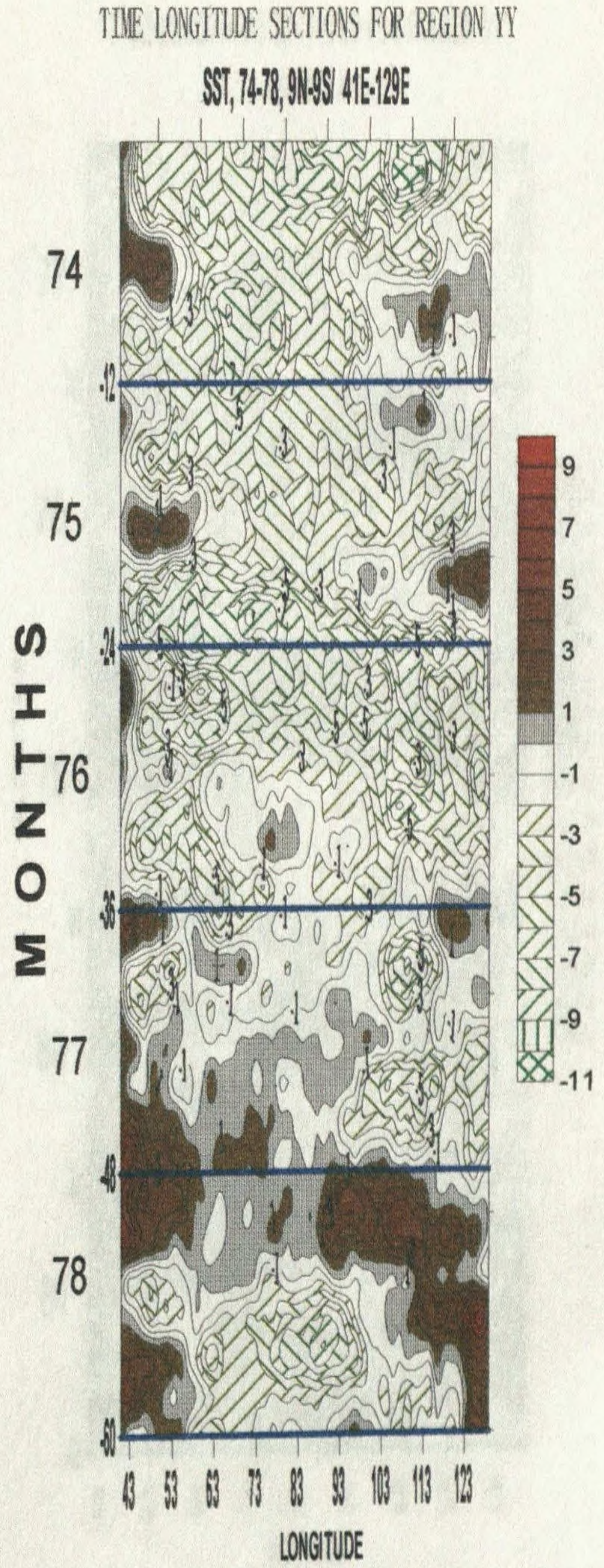


Fig.20 Time Longitude section for Region YY SST during the time period (1974-1978) (9^0 N-9^0 S , 41^0 E-129^0 E), Contour intervals are 0.2^0 C
Positive anomalies are shaded

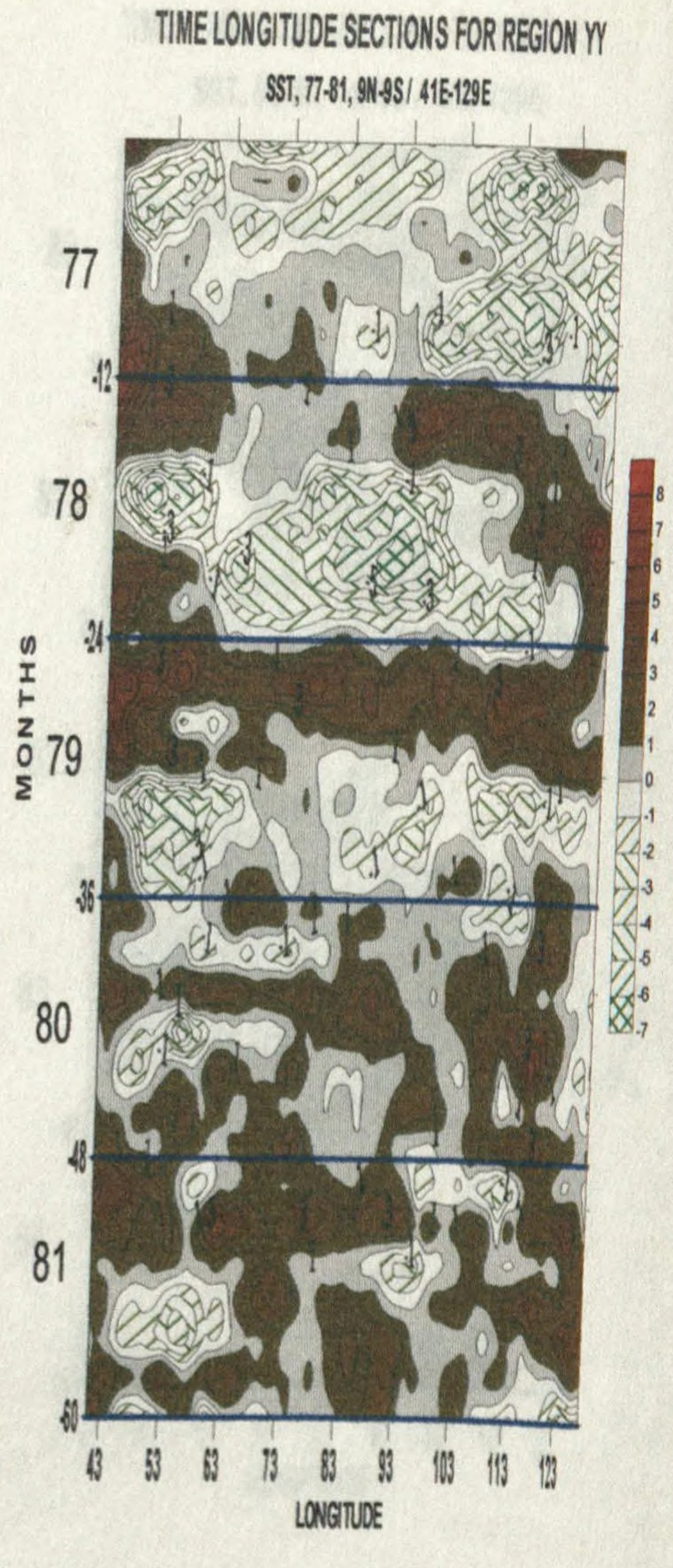


Fig.21 Time Longitude section for Region YY SST during the time period (1977-1981) (9^0N-9^0S , 41^0E-129^0E), Contour intervals are 0.2 ^{0}C
Positive anomalies are shaded

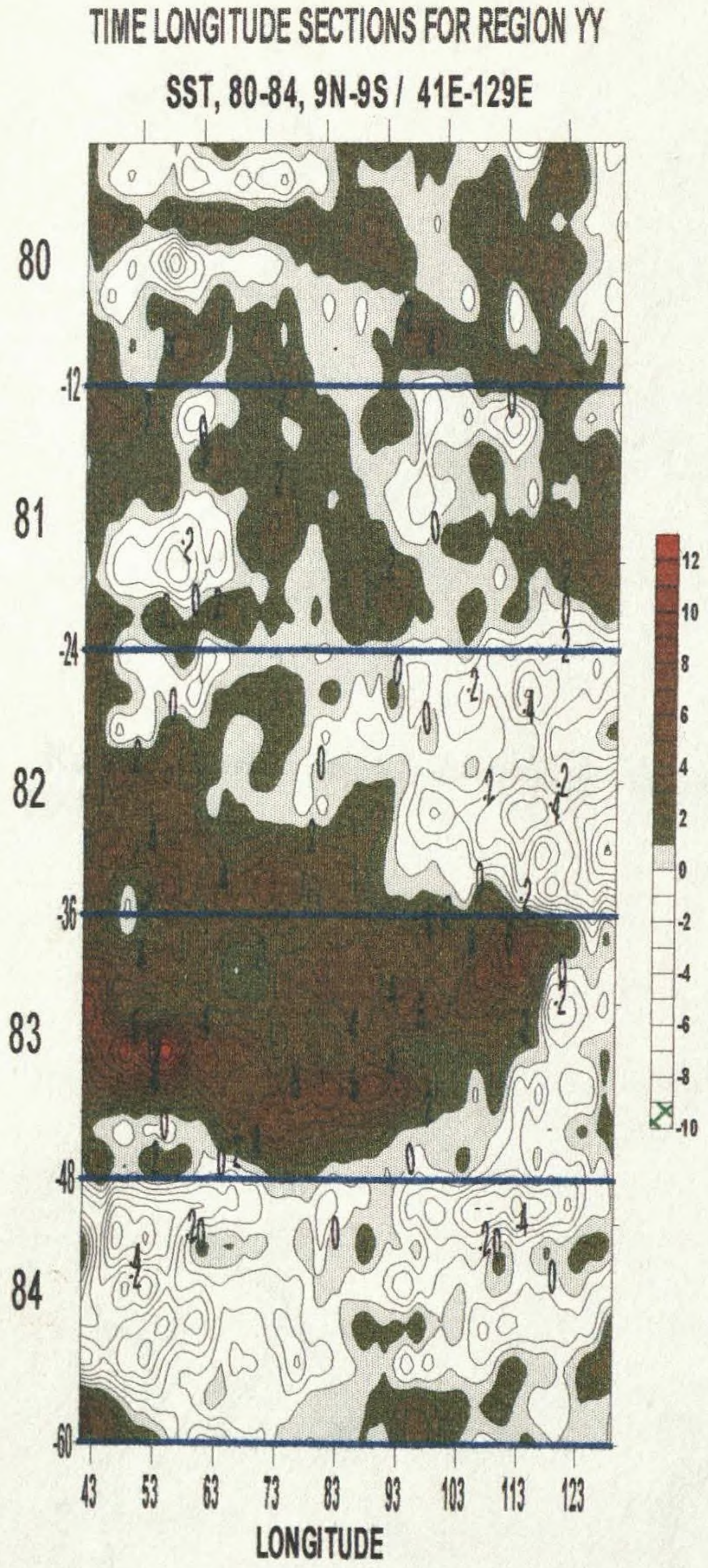


Fig.22 Time Longitude section for Region YY SST during the time period (1980-1984)
(9^0N-9^0S , 41^0E-129^0E) Contour intervals are 0.2 ^{0}C
Positive anomalies are shaded

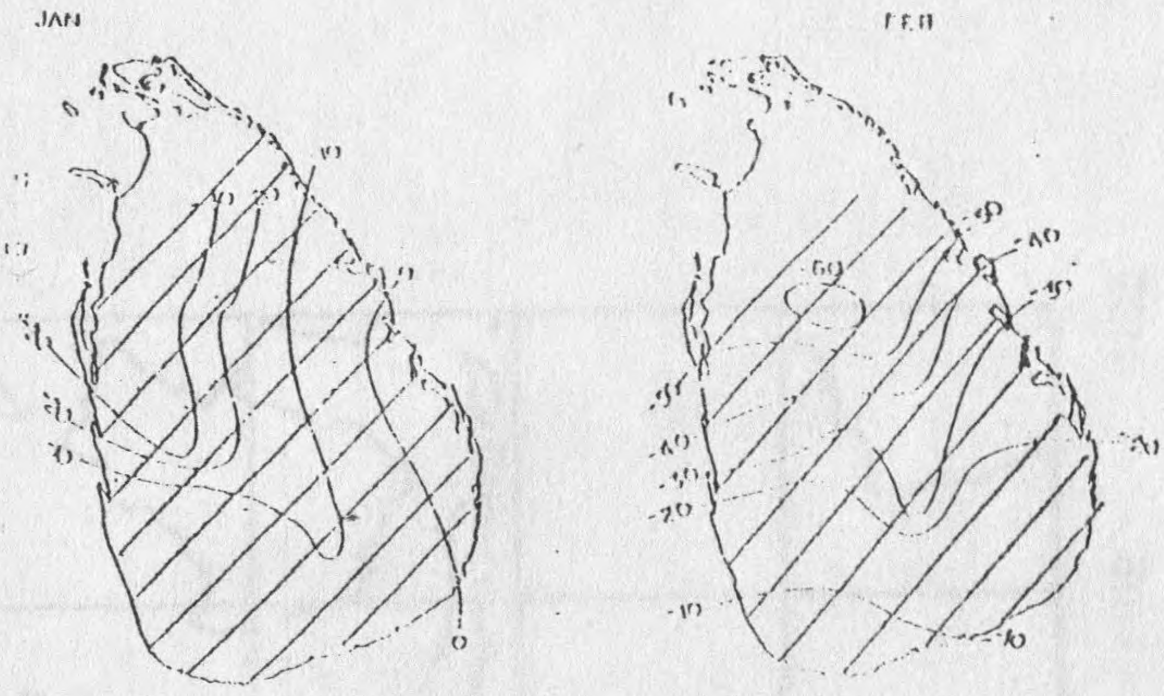


Fig. 23 Rainfall Index distribution in the month of January and February during El-Nino year

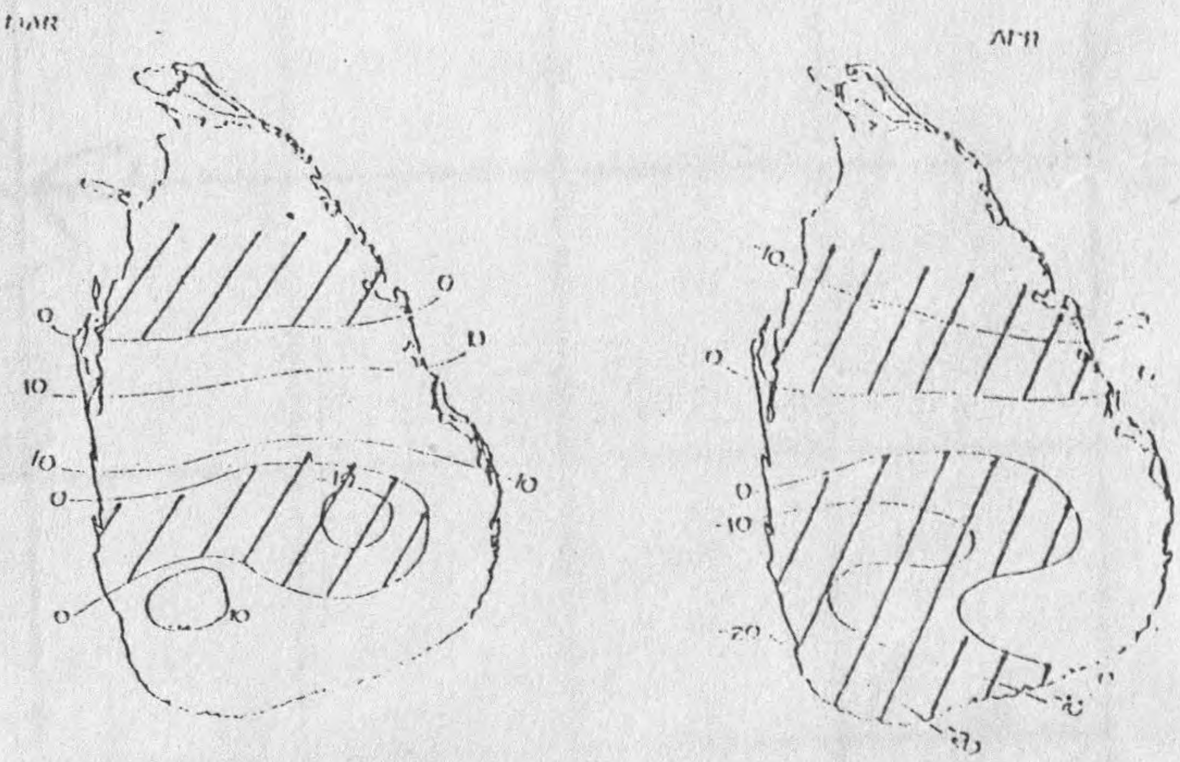


Fig. 24 Rainfall Index distribution in the month of March and April during El-Nino year.

Negative anomalies are dashed

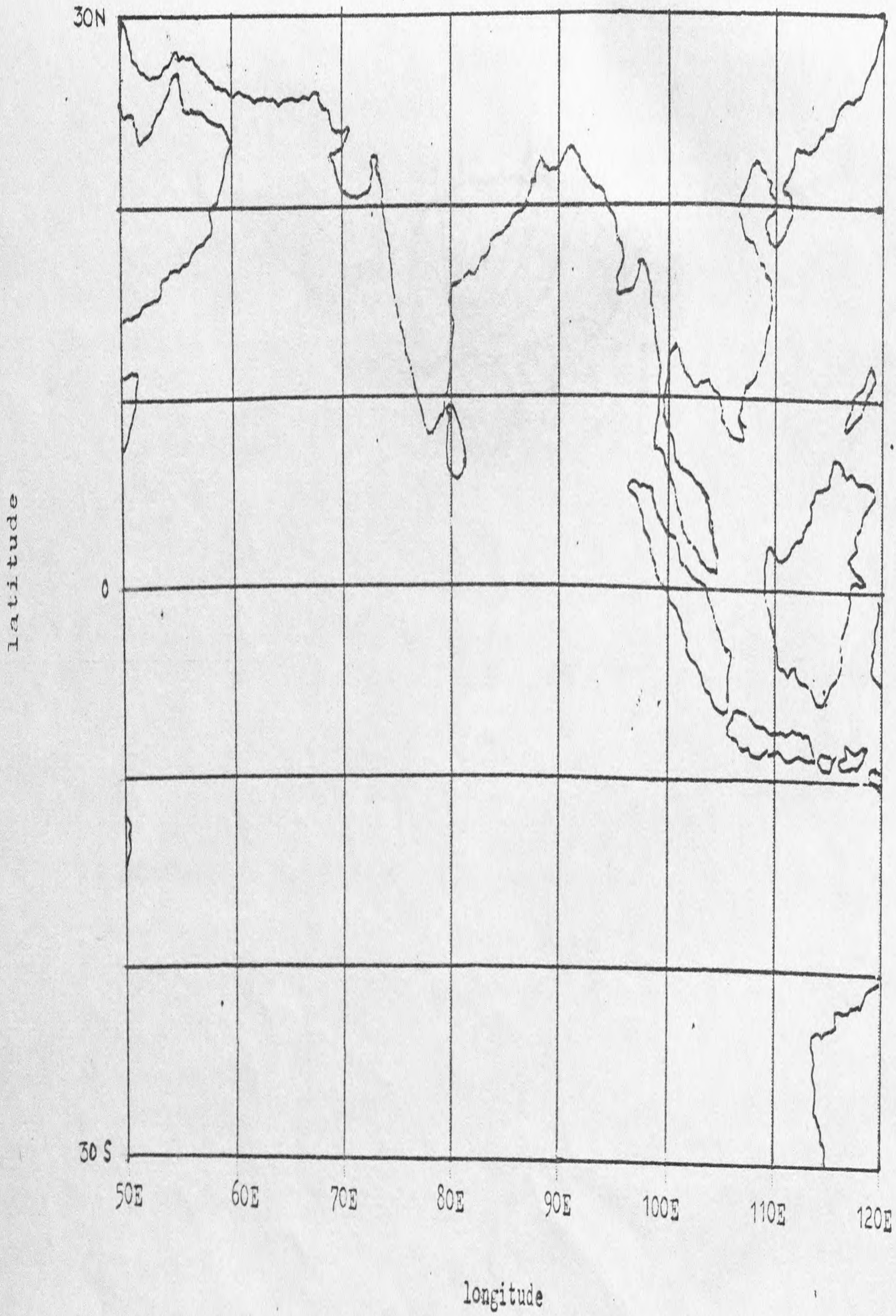


Fig. 25 Area covered this study , 30N-30S Latitudes and 50 E -120 E Longitudes.

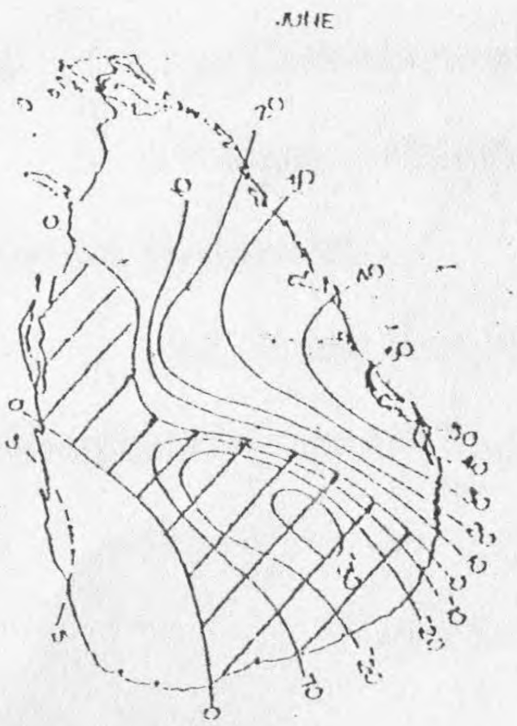


Fig. 26 . Rainfall Index distribution in the month of June during El-Nino year.

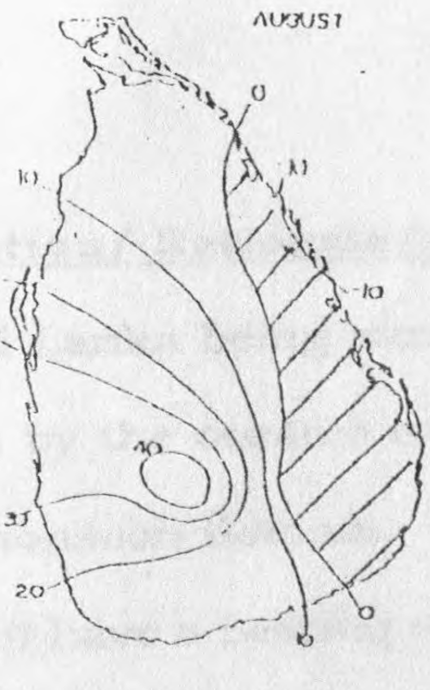


Fig. 27 Rainfall Index distribution in the month of August during El-Nino year.

(B) Summary

Title: The Climate trends over south Asia and their influence on Sri Lanka. (Contract Number: RG / 96 / P / 03)

Research Institute:

The Open University of Sri Lanka, Nawala, Nugegoda.

Chief scientific investigator:

Dr. W. L. Sumathipala, Department of Physics,
The Open University of Sri Lanka
Nawala
Nugegoda.

Period of Contract:

Date of award: 01/04/1996
Date of completion: 31/03/2000

Introduction/ Rationale/ Justification

Sri Lanka being surrounded by ocean its weather & climate must be influence by the oceanic condition. In addition Sri Lanka is situated in the Asiatic monsoon domain. Therefore the changes taking place in the whole region will have a bearing on climate condition on Sri Lanka.

El-Nino is considered to be one of the strongest signals of the changing climate scenario. Although the birthplace of El-Nino is identified as the Pacific ocean its influence is felt globally and more prominently over the Asian monsoon domain. There are studies to show that Indian Ocean play a crucial role at the development phase of El-Nino or even modifying the strength of it. Even at a El-Nino period the ocean condition around Sri Lanka can modify large scale El-Nino signal.

In this study influence of the sea surface Temperature (SST) and outgoing long wave radiation (OLR) change in the region on Sri Lanka rainfall distribution of Sri Lanka is analyzed. Further spatial and temporal fluctuations of SST and OLR in the Indian Ocean and its influence on El-Nino phenomenon is examined. Also the relationship between El-Nino and rainfall fluctuation during Southwest monsoon, Northeast monsoon and inter monsoons and on different region of the country is studied.

Material and Method

OLR data was extended from global data set which included data at 2.5° x 2.5° latitude and longitude grid spacing for the duration of 16 years from 1974 to 1990. Global SST data at 2° x 2° latitude longitude interval was available from 1971 to 1990. Rainfall data at main meteorological stations from 1901 to 1994 were used in this study.

These three data types was made into appropriate sets and time series analysis, special and temporal correlation and harmonic analysis techniques were used in the study. Apart from the analysis, data were plotted as time latitude and time longitude cross section in order to see the propagating climate signals in the region.

Result and Conclusion

From the study it was possible to Establish the following.

During an El-Nino year high SST (.>29°C) life just over the equator and spreads over a large area in the Indian ocean as compared to normal year. Several global El-Ninos showed negative SST anomaly in the Indian Ocean. This indicates that Indian Ocean is not in phase with the Pacific Ocean always on SST changes. During La-Nina years positive SST anomaly was found in the most of the months in the Indian Ocean. Clear eastward movement of positive and negative SST anomaly signals was observed in the western Indian Ocean towards the Western Pacific Ocean prior to an El-Nino as well as La-Nina events.

Correlation between SST as well as OLR over several regions in the Indian Ocean and the rainfall of Sri Lanka during the southwest and northeast Monsoon periods have a significant relationship. After year 1982 an increasing trend was observed in the OLR field in the region. Low convective activity was observed north of the equator while south of the equator showed high covective activity during El-Nino year. Clear northward movement of positive and negative OLR anomaly signals were observed in the Southern Hemisphere during El-Nino and La-Nina events. El-Nino as well as La-Nina phenomenon greatly affect the northeast monsoon rainfall. Quasi-biennial oscillation was prominent in the wetzone rainfall while in dryzone rainfall annual oscillation was dominant. Decreasing trend In rainfall was observed in the dryzone during 1918 - 1952 and 1963-1978. Decreasing trend of rainfall was observed in the wetzone during 1928-1953 and 1961-1985 while decreasing trend of rainfall was observed in the wet zone during 1928 -1953 and 1961-1985.

PUBLICATIONS

- **Punyadeva, N.B.P., and W.L Sumathipala. 1997**. Variation of OLR in the Indian Ocean and its relationships to rainfall of Sri Lanka. Proceedings of the 53rd Annual Sessions, of SLAAS, December 1997
- **Punyadeva, N.B.P., and W.L Sumathipala. 1998.** Variation of Sea Surface Temperature (SST) in the Indian Ocean during El-Nino year, Proceedings of the 14th Annual Sessions, IPSL, March 1998

- **W. L. Sumathipala, and N.B.P Punyadeva. 1998. Variation of Rainfall of Sri Lanka in relation to El-Nino, Proceeding of the 14th annual sessions, IPSL, March 1998**
- **Punyadeva, N.B.P and W. L Sumathipala 1998.** Behavior of OLR field over the Indian Ocean during El-Nino year and Normal year. Proceedings of 54th Annual Sessions of SLAAS, December 1998
- **Punyadeva, N.B.P., and W.L. Sumathipala. 1999.** Behavior of longitudinal movements of OLR field over the Indian Ocean during the time period of 1974 -1990. Proceedings of 55th Annual Sessions, of SLAAS, December 1999

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