IMPACT OF CONVECTION OVER THE EQUATORIAL TROUGH ON INDIAN SUMMER MONSOON ACTIVITY

by

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(2010-20-118)

THESIS

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DECLARATION

I, hereby declare that this thesis entitled **'IMPACT OF CONVECTION OVER THE EQUATORIAL TROUGH ON INDIAN SUMMER MONSOON ACTIVITY'** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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CERTIFICATE

Certified that this thesis entitled **'IMPACT OF CONVECTION OVER THE EQUATORIAL TROUGH ON INDIAN SUMMER MONSOON ACTIVITY'** is a record of research work done independently by Ms. Gopika S. (2010-20-118) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

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“I dedicate this Thesis work to my loving parents”

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SYMBOLS AND ABBREVIATIONS

AS	Arabian Sea
BoB	Bay of Bengal
BM	Break in Monsoon
CDAS	Climate Data Assimilation System
DMI	Dipole Mode Index
EEP	Eastern Equatorial Pacific
EET	Eastern Equatorial Trough
ENSO	El-Nino Southern Oscillation
EPI	Eastern Peninsular India
EQUINOO	Equatorial Indian Ocean Oscillation
ERSST	Extended Re-constructed SST
ET	Equatorial Trough
FORTRAN	Formula Translation
GMT	General Mapping Tool
GPCP	Global Precipitation Climatology Project
GrADS	Grid Analysis And Display System
HadISST	Hadley Centre Global Sea Ice and SST
ICOADS	International Comprehensive Ocean Atmosphere Dataset
IITM	Indian Institute of Tropical Meteorology
IMD	Indian Meteorological Department
IOD	Indian Ocean Dipole
IR	Infrared
ISMR	Indian Summer Monsoon Rainfall
ITCZ	Inter Tropical Convergent Zone
JAXA	Japan Aerospace Exploring Agency
JJAS	June, July, August and September

LLJ	Low Level Jet Stream
MOK	Monsoon Onset over Kerala
NASA	National Aeronautical and Space Administration
NCAR	National Centre for Atmospheric Research
NCEP	National Centre for Environmental Prediction
NCI	North Central India
NEI	North East India
NIO	North Indian Ocean
NMI	North mountainous India
NOAA	National Ocean and Atmospheric Administration
NWI	North West India
NWP	Northwest Pacific
OLR	Outgoing Longwave radiation
PM-ESIP	Passive Microscopic ESIP
RSMC	Regional Specialized Meteorological Center
SEEIO	South Eastern Equatorial Indian Ocean
SOI	Southern Oscillation Index
SPI	Southern Peninsular India
SST	Sea Surface Temperature
TMI	Tropical Rainfall Measuring Mission Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
WCI	Walker Circulation Index
WEIO	Western Equatorial Indian Ocean
WEP	Western Equatorial Pacific
WPI	Western Peninsular India

INTRODUCTION

CHAPTER 1

INTRODUCTION

The word 'monsoon' is derived from the Arabic word '*mausam*' for season and the distinguishing attribute of the monsoonal regions of the world is considered to be the seasonal reversal in the direction of the wind (Ramage, 1971). No solitary event is more influencing India than the approaching of the monsoon season. Halley (1686) defined monsoon as the seasonal reversal of steady and sustained surface winds, which blows from southwest during the summer monsoon (June-September) and from northeast during the winter monsoon (November-February). Indian summer monsoon is starting from Kerala coast, which further propagate northwards and most of the annual rainfall in India occurs during this period. According to Krishnamurthy and James (2002), monsoon is the wind system over India and adjoining oceanic regions that blows from the southwest half the year and from the northeast during the other half. The seasonal reversal of the wind direction occurring in May brings copious moisture from the warm waters of the tropical ocean to the Indian subcontinent through southwesterlies.

Indian monsoon has three unique features which distinguishes each one from the other.

1. Monsoon onset over Kerala (MOK)
2. Active/Break cycle within the monsoon life cycle
3. Amount of rainfall received.

The commencement of Indian monsoon season is noticeable by its beginning over Kerala coast which is accompanying with lot of fluctuations in the large-scale dynamical parameters as well as native moisture patterns. Forecast of monsoon onset over Kerala (MOK) is very much important because of its sociological and commercial influence. India Meteorological Department (IMD) has been announcing MOK subjectively based on the rainfall that acquire over Kerala. The declaration of MOK is based on the rainfall availability over Kerala, value of Outgoing Longwave Radiation (OLR) as well as the strength and vertical extent of the lower tropospheric zonal wind.

Indian monsoon system is extremely asymmetrical and flexible at intra-seasonal and inter-seasonal timescales. The northward progression of the monsoon is symptomatic of a large scale transition of a deep convection from the equatorial to continental regions (Webster *et al.,* 1998, Pai and Rajeevan, 2007). By middle of July monsoon reaches all over India. Irregular circulation of monsoon wind and rainfall can unfavorably disturb the agricultural sector. Unpredictability in Indian summer monsoon can be considered on the basis of active and break spells of monsoon. Continuous and good amount of rainfall is the result of an active spell while breaks are the interrupted rainless intervals in the monsoon and which are related to the movement of monsoon trough. Long and intense break spells can influence monsoon rainfall up to a large extent (Gadgil and Joseph, 2003). Frequent and sustained break situations can lead to drought circumstance.

During the summer monsoon months, monsoon depressions and monsoon lows forms over the north of Bay of Bengal (BoB) and adjoining land areas, move towards the north western parts of India. Cyclones in the North West Pacific (NWP) are also important when considering the monsoon rainfall over India. The distribution of summer monsoon rainfall is influenced by tropical cyclone in NWP and 60 per cent of the tropical cyclones in the region occur during summer monsoon season. The number of tropical cyclones forming in the northwest and west–central Pacific is about 1.33 times higher during weak monsoon years compared to strong monsoon years. Secondly, there is a greater tendency for the tropical Pacific cyclones to recurve and move northward (north of 20°N) during weak monsoon years relative to strong monsoon years (Vinay and Krishnan, 2005).

Indian summer monsoon rainfall critically affects India's agriculture and economy which provides about 60–80 % of the mean annual rainfall over India. The yield of rain fed region in India is substantially reduced during drought. Indian summer monsoon exhibits a wide spectrum of variability, on daily, sub-seasonal, inter-annual, decadal and centennial time scales. An Equatorial Trough (ET) develops in the eastern boundary of Indian Ocean during summer monsoon. The convective activity over this trough affects the pattern and trend of Indian summer monsoon. Thus the prediction, forecasting and monitoring of summer monsoon more challengeable.

According to meteorological records the mean date of monsoon onset over Kerala is around 1st June. Agricultural operations are based on the amount of monsoon and onset of monsoon. Precise forecasts help farmers to select the correct variety of seeds and deciding the sowing time for a better yield. This study is pointing out an important scientific explanation about decreasing (increasing) rainfall during a break (active) period of Indian summer monsoon. These results will help the forecasters for a better prediction.

This study is taken with the following objective of establishing relationships between convective activity over equatorial trough and active or break cycle over India. Relationship between convective activity over equatorial trough and number of convective system over North Indian Ocean (NIO). Relationship between convective activity over equatorial trough and number of convective system over North West Pacific (NWP).

Concurrent relationship of Sea Surface Temperature (SST) over different Indo-Pacific regions, Southern Oscillation Index (SOI) and Walker Circulation Index (WCI) on the monsoon activity over the Indian subcontinent were also attempted to establish as part of the present study.

REVIEW OF LITERATURE

CHAPTER 2

REVIEW OF LITERATURE

2.1 Summer monsoon season of India

The monsoonal region delineated on the basis of significant change in the wind direction between winter and summer extends over a large part of the tropics, namely, 25° - 35°N, 30° - 170°E (Ramage, 1971). It is distinguished that maximum of the precipitation in India happens throughout the June-July-August-September (JJAS) season so it is called Indian great monsoon season. The summer monsoon gives about 80 % of the mean annual rainfall for the various meteorological subcontinent is one of outstanding meteorological phenomena of the Indian meteorology (Ananthakrishnan and Pathan, 1981).

According to a hypothesis by Charney and Shukla (1981), the seasonal monsoon rainfall over India has potential predictability, because it is forced by the slowly varying boundary conditions such as SST, soil moisture, sea ice and snow.

The summer monsoon rainfall first reaches in the southern peninsular India, so the onset is determining based on the rainfall over Kerala between late May and early June. Monsoon onset forecasted for 2015 by IMD is represented in Fig. 1. Pearce and Mohanty (1984) showed that the major precursor for monsoon onset is the build-up of moisture up to mid-troposphere about 2 weeks in advance of MOK. Because of the importance of MOK in the annual calendar, many investigations have been undertaken in India as well as by the international scientific community to unravel features and variability of MOK.

The Indian monsoon is now understood to be an integral part of the global climate system involving coupled atmosphere-land-ocean interactions (Webster *et al.* 1998).The forecast of the monsoon rainfall and flow is critical for India and absolutely significant for other parts of the globe because of the monsoon's relation with such components.

Flatau *et al.* (2002) studied the delayed monsoon onset over India. Ramesh and Uma (2004) suggested that the mid monsoon months of July and August together contribute about 61 % of the mean seasonal rainfall. Hence prolonged breaks in these two mid monsoon months can create deficit monsoon or drought conditions. Prasad and Hayashi (2005) have examined the onset and withdrawal phases of monsoon over India. Most of the indicators of Indian summer monsoon are strengthening of winds, seasonal reversal in temperature and variability in the position of monsoon trough. Goswami and Xavier (2005) emphasized the change in mid / upper tropospheric meridional temperature gradient as an important parameter for objectively defining MOK.

There are many ways of predicting the MOK that is suggested by many scientists. To forecast monsoon, the spatial and temporal distribution of rainfall during the season, monsoon intensity and amount of monsoon rainfall during the season and MOK are to be considered (Pai and Rajeevan, 2007). These are the accepted criteria followed by IMD for their prediction. The guidelines followed by IMD for declaring the onset of monsoon over Kerala is given below.

1. Rainfall

If after 10^{th} May, 60 % of the available 14 stations enlisted, viz. Minicoy, Amini, Thiruvananthapuram, Punalur, Kollam, Allapuzha, Kottayam, Kochi, Thrissur, Kozhikode, Thalassery, Kannur, Kudulu and Mangalore report rainfall of 2.5 mm or more for two consecutive days, the onset over Kerala be declared on the 2^{nd} day, provided the following criteria are also in concurrence.

2. Wind field

Depth of westerlies should be maintained up to 600 hPa, in the box equator to Latitude 10° N and Longitude 55° - 80° E. The zonal wind speed over the area bounded by Latitude 5° - 10° N, Longitude 70° - 80° E should be of the order of 15-20 knots at 925 hPa. The source of data can be Regional Specialized Meteorological center (RSMC) wind analysis/satellite derived winds.

3. Outgoing Longwave Radiation (OLR)

INSAT derived OLR value should be below 200 Wm^{-2} in the box confined by Latitude 5° - 10°N and Longitude 70° - 75°E.

The shift of mean convective heat source to the AS or BoB from the central equatorial Indian Ocean in the month of May also decides fate of the Indian summer monsoon rainfall (ISMR) (Simon *et al.,* 2008).

The Indian monsoon is identified to have a robust relationship with El Niño and the Southern Oscillation (ENSO) events through ocean-atmosphere interactions. Whether the monsoon impacts ENSO or ENSO impacts monsoon is also of significant research attention. With similar relations with the Indian Ocean, Eurasian snow and the climate of other parts of the globe. Ghosh *et al.* (2009) reported that the daily rainfall amounts and occurrences of the ISMR show spatial variations due to rapid urbanization, industrialization and deforestation. Revadekar and Preethi (2012) showed the significant impact of extreme monsoon rainfall on food grain yield over India through statistical analysis.

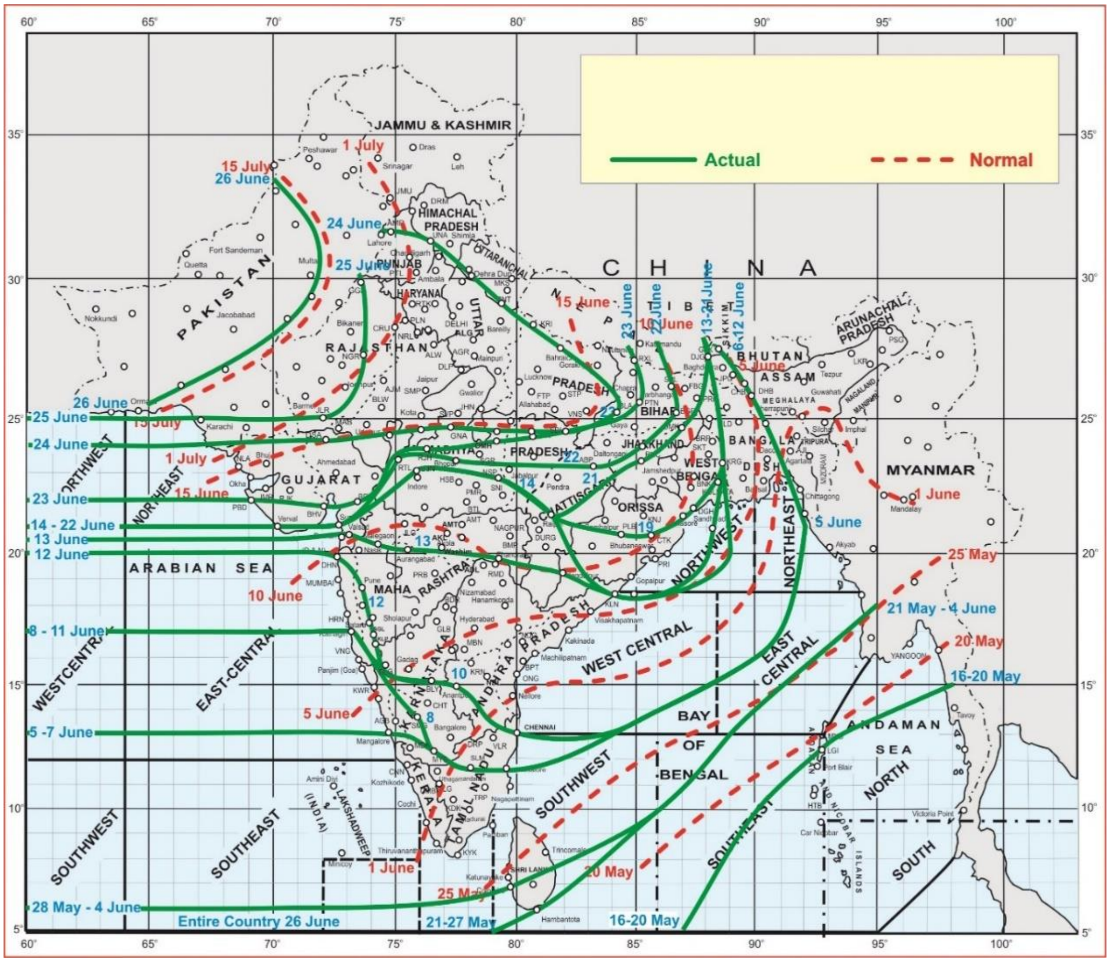

Figure 1. The Indian summer monsoon progress in 2015. (Image courtesy http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm)

2.2 Inter-annual variation

There is large inter-annual variability in the formation of convective systems and in the case of the Northwest Pacific (NWP), this variability is related to the El-Nino Southern Oscillation. The Presence of anomalous equatorial westerlies in the western Pacific and SST anomalies in the central and eastern equatorial pacific are associated with part of the inter-annual variability of tropical cyclone activity in the North West Pacific (Chan, 1985).

Krishnamurthy and Shukla (2000) prepared a time series of ISMR for the period 1901-70 based on a gridded rainfall data set generated from observations at more than 3700 stations over India. Since they included the rainfall over the hilly regions of northeast India in the area averaged rainfall, the long term mean of their JJAS ISMR is 923 mm with a standard deviation of 87 mm. The dominant pattern of the inter-annual variability is obtained by examining the composites of JJAS seasonal rainfall anomalies for strong (flood) and weak (drought) monsoon years. The large inter-annual variability of Indian monsoon may cause marked sea level change due to fluctuation of monsoon wind, freshwater flux, heat fluxes and river runoff into the BoB (Han and Webster, 2002).

Goswami *et al.* (2006) demonstrated that the frequency and intensity of extreme rainfall events during the summer monsoon season have increased over the central India since the middle of the twentieth century whereas the low and moderate rainfall events have substantially decreased.

2.3 Intra-seasonal variability

The variation between active and break periods and the northward propagations of the Inter Tropical Convergent Zone (ITCZ) are very important when considering the intra-seasonal variability. Charney and Shukla (1981) proposed that the inter-annual variability of monsoon rainfall is largely determined by changes in the slowly varying boundary conditions, the predictability of the monsoon rainfall depends on knowing whether droughts and floods over India (inter-annual variability) are the manifestation of large-scale persistent rainfall anomalies, or are due to a change in the nature of the intra-seasonal variability.

2.4 Active and break phases

According to Raghavan (1973), After the onset of break monsoon, atmospheric condition undergo steady changes over the plains, gradually improving to generally cloudless skies and rainless days also the surface temperature rises to above normal value. The years with longer duration epochs of active Southern hemisphere ET, the seasonal summer monsoon rainfall remains below normal (De *et al.,* 1995). According to Cadet and Daniel (1988), Weak spells of the average rainfall at 15 stations distributed throughout India considered as breaks in the monsoon. Webster *et al.* (1998) use the term break, to denote weak spells of convection and 850 hpa zonal winds over a large-scale region.

Krishnan *et al.* (2000) define break days as days with positive OLR anomalies over northwest and central India (i.e., only over the western part of the monsoon zone), provided the average OLR anomaly over 73° - 82° E, 18° - 28° N exceeds 10 Wm^{-2}.

There are many examples of years with excess (strong monsoon) or deficit (weak monsoon) during which India as a whole receives well or less summer monsoon seasonal rainfall, respectively. In addition to year-to-year unevenness, there is also great spatial and intra-seasonal variability of the summer monsoon rainfall in India. Even inside a period, there is substantial disparity, both in case of temporal and spatial in the rainfall over India. The primary reason for this variability is that the rainfall is accompanying either with the strengthening and/or dislocation of the monsoon trough (or ITCZ) over northern India or with the monsoon depressions that form over the connecting seas and travel over land. The intra-seasonal variation is characterized by "active" spells (high rainfall) and "break" spells (weak or no rainfall) over central India and the west coast, each phase lasting for a few days. The intra-seasonal and inter-annual variability of the summer monsoon has a remarkable socio-economic influence on India.

Goswami and Mohan (2001) define breaks on the basis of the strength of the 850-hpa wind at the single grid-point. Annamalai and Slingo (2001), use the term break to denote weak spells of the daily all-India average rainfall. In intervals of drought, when northwesterly and westerly winds interrupt the monsoon in North- Western and Central India, it (the trough of low pressure) is pushed northward to the foot of the hills.

Rao *et al.* (2004) suggested that drying of the upper troposphere in transition from 'active' to 'break' monsoon conditions. Active-break cycle is an essential part of the monsoon intra-seasonal variability and is also observed in the model simulations even with climatological SST forced simulations. It will and should continue to attract the attention of investigators

Ramesh and Uma (2004) defined a new criterion for the break in monsoon conditions over the Indian subcontinent based purely on the all India monsoon rainfall, which they considered to be truly representative of the monsoon conditions over the Indian subcontinent. According to their criterion, they classified a break as one when the daily all India rainfall in the months of July and August is less than 9 mm for three consecutive years; similarly they classified active conditions as days when the all India daily rainfall is more than 15mm and persists for three days. The break in the Indian summer monsoon can occur almost every year. The rainfall patterns undergo a striking change: the eastern and Nepal Himalayas and South Eastern parts of peninsula get abnormal rainfall.

According to Ramesh *et al.* (2005), most (about 73 %) of the break in monsoon (BM) events were associated with convective activity (rainfall more than 30 mm/ pentad) over the ET region. On an average, there are 7 days of active and break events during the period July and August.

Wang *et al.* (2005) showed that western equatorial Indian Ocean (WEIO) plays a critical role in predicting the antecedents of the active/break monsoon conditions over the Indian subcontinent. Their study revealed that the decreasing westward wind speed along the equator favored wind convergence in the western equatorial Indian Ocean. This in turn lead to moistening of the boundary layer increasing the convective energy of the source air and modifying the vertical stratification. Thus convection could occur again and the surface moisture convergence increases rapidly in the central and western equatorial Indian Ocean due to westward decrease of zonal equatorial wind and confluence of equatorial winds. The moisture convergence in the central equatorial Indian Ocean is reinforced by the equatorward flows and the convection. They also found that the local Ocean - Atmosphere interaction also plays a significant role. When the central equatorial Indian Ocean is dry, the downward solar radiation increases because there are fewer clouds, while the heat loss from evaporation and entrainment decreases because wind speed decreases.

The number of tropical cyclones forming in the northwest and west – central Pacific is about 1.33 times higher during weak monsoon years compared to strong monsoon years. Secondly, there is a greater tendency for the tropical Pacific cyclones to recurve and move north ward (north of 20°N) during weak monsoon years relative to strong monsoon years (Vinay and Krishnan, 2005).

It was found that in the deficit years and prolonged breaks in monsoon conditions, the systems (about 69 %) formed further south than in the case of excess monsoon years, the maximum difference in the shift of latitude and longitude was observed in the peak monsoon month of July indicating the significant influence of the convective systems over the northwest Pacific Ocean on the monsoon activity over the Indian subcontinent (Ramesh *et al.*, 2009a).

Changes in SST is responsible for break monsoon condition over India, (Ramesh *et al.,* 2009b, Ramesh and Sankar, 2010). On an average, there are seven days of active and break events during the period July and August. Number of break days is significantly correlated with the Indian summer monsoon rainfall (Rajeevan *et al.*, 2010).

2.5 Indian Ocean and Indian monsoon

Saha (1974) concluded that the higher SST in the Indian Ocean region would lead to higher evaporation and this will release more moisture into the atmosphere which will result in good monsoon. This opinion was contradicted by Weare (1979) and proposed that warmer Arabian Sea (AS) or Indian Ocean is weakly associated with the decreased rainfall over most of the meteorological subdivisions by performing an empirical orthogonal functional analysis on the Indian Ocean.

Shukla *et al.* (1977) studied the monthly sea surface temperature and surface wind pressure into Central Arabian Sea for the period 1901-60 and found significant Correlation between SST during July and Rainfall over central and western Indian during August, between surface wind speed during July and rainfall during July, but insignificant correlation found between surface wind speed during July and rainfall during August.

The SST is warmest over most of the Indian Ocean north of 10°S when the southwest monsoon begin in India at the end of May. Based on satellite data and observed OLR, Graham and Barnett (1987), hypothesized that organized atmospheric convection is inhibited below a threshold SST of 28°C. When the SST exceeds the threshold, the convection is associated more with the convergence of moist air rather than evaporation.

Mishra (1981) analyzed the SST variability over the North Indian Ocean during south west monsoon in the years of 1977, 1978 and 1979 using the satellite derived SST data. The study discovered that the beginning of cooling in surface waters over the AS is associated with the advances of the south west monsoon. Joseph and Pillai (1984) studied the relationship between SST values over three regions (two regions are in the AS and one region is in the BoB) with the monsoon rainfall over India. They suggested that SST exhibited a prominent three year periodicity in addition to the annual variation.

Indian Ocean, associated with particular types of inter-annual variability of climate, the first is associated with ENSO, and the second with the tropospheric Quasi-Biennial Oscillation, north Indian Ocean intra-seasonal oscillation and spatial pattern of the long term trend of SST variation. (Godfrey, 1995). According to Chambers (1999), SST and wind data suggest that Indian Ocean warming has occurred during several previous El-Niño events, particularly during 1982 and 1987. Based on these observation it is suggested that warming bigins with wind forced rossby waves in the south East Indian Ocean associated with the southern oscillation similar to the forcing of kelvin waves which precede El-Niño in the Pacific.

Clark *et al.* (2000) discovered a long-lead predictive relation between the Indian Ocean SST and the monsoon rainfall. They found a significant positive correlation (0.53) between the winter (December, January and February) SST in the north AS (around 66°E, 20°N) and the subsequent summer JJAS monsoon rainfall over India (ISMR index). They also found a strong positive correlation (0.87) between the JJAS ISMR index and the SST in the central Indian Ocean (around 86°E, 4°N) during the preceding September- November period.

In the Indian Ocean, the region of SST greater than 28°C occurs south of the equator in January and expands to a large region (20°S - 20°N) during February-April (Krishnamurthy and Kirtman ,2001).

Tschuck *et al.* (2004) suggested that SST anomalies in the equatorial Indian Ocean, shows no clear reduction of the all-India rainfall with increasing temperatures. Earth is now absorbing 0.85 ± 0.15 Wm^{-2} more energy from the sun than it is emitting to space. This imbalance is confirmed by precise measurements of increasing ocean heat content over the past 10 years (Hansen *et al.,* 2005). About 93 per cent of the excess heat energy stored by the earth over the last 50 years is found in the ocean (Church *et al.,* 2011).

Indian Ocean is consistently warming and its warm pool is expanding, particularly in the recent decades (Rao *et al.,* 2012).

The presence of a relatively strong surface convergence over the AS, due to the presence of a strong zonal gradient in SST, which accelerates the upward motion of the moist air, results in a relatively faster response in terms of the local precipitation anomalies over the AS than over the BoB and South China Sea (Roxy *et al.,* 2013).

SST over the Indian Ocean and west Pacific show variability on intra-seasonal timescales, with a change of up to 1–2^0C within a week or two (Roxy, 2013). Indian Ocean SST plays an important role in the variation of the global climate, because the absolute value of the SST high over the Indian Ocean, even small change in the Indian Ocean SST can produce significant impacts on global climate (Yanh Zhou *et al.,* 2014). Magnitude of SST warming trend is significantly stronger during the summer monsoon season than during the other seasons (Swapna *et al.,* 2009).

But this result was challenged by Roxy *et al.* (2014), based on his findings Indian Ocean has been warming consistently for over century and at a faster rate than any other region of Tropical Ocean, and this may weaken the Indian monsoon circulation. SST warming is caused by atmospheric processes, it plays a vital role in regulating the mean climate and variability of the Indian monsoon, as well as the dynamics over the tropics.

During the past half-century it was observed that continuously increasing warming over the Indian Ocean warm pool and Indian Ocean Sea Surface Temperature warming was the strongest and most robust warming signal around the global ocean (Lu Dong *et al.,* 2014).

2.6 Indian monsoon and Inter tropical convergence zone (ITCZ)

The monsoon is considered as a manifestation of the seasonal migration of the inter-tropical convergence zone, In the steady state, it is expected that the ITCZ over the oceans will be located over the latitude at which the SST is maximum (Charney, 1969).This hypothesis associates the monsoon with a system special to the monsoonal region, the monsoonal regions differ only in the variability of the seasonal migration of the basic system (ITCZ/ET).

The intense convective zones are associated with the east-west ITCZ over the north equatorial tropical Pacific Ocean and with the South Pacific convergence zone (SPCZ) that grades in the northwest-southeast direction over the western tropical Pacific Ocean. Air ascending over the equatorial tropical convergence zone descends above the shallow cell associated with the heat trough (Raghavan, 1973).

By way of analyzing satellite imagery and the location of the monsoon trough, Sikka and Gadgil (1980) proposed that the summer monsoon rainfall system in the Indian region consists of intense low level convergence and deep moist convection and has dynamical and thermo-dynamical characteristics similar to the ITCZ.

The ITCZ is strong over the tropical Pacific Ocean during the northern hemispheric summer. As the season changes from June , July and august to December, January and February, the intense convective activity moves further southeast from the Indian region to the south Pacific Ocean through the Oceanic Continent. The seasonal movement of the rainfall coincides with the movement of the convective zones observed in the OLR and also indicated by the satellite imagery of reflectivity (Meehl, 1987).

2.7 Indian Ocean Dipole (IOD) and El-Niño

The El Niño phenomenon, normally mentioned to as El-Niño Southern Oscillation (atmospheric component of El-Niño) or ENSO, is a substantial disturbance in the ocean-atmosphere coordination of the eastern Pacific Ocean that has important significances on the ecology and environment (Fig. 2). The related atmospheric change is called the Southern Oscillation, referring to large scale seesaw in atmospheric pressure between the south eastern tropical Pacific and north of Australia (Bjerknes, 1966). According to Kumar *et al*. (1999), the link with El Niño has weakened in the last decade, and in fact the ISMR anomaly was positive in the recent intense warm event of 1997.

IOD is defined as an irregular oscillation of SST in which western Indian Ocean becomes alternatively warmer and colder than the eastern part of the ocean. It is normally characterized in terms of anomalous cooling of SST in south eastern equatorial Indian Ocean and anomalous warming of SST in western equatorial Indian Ocean. Saji *et al.* (1999) proposed an index for quantifying Indian ocean dipole, it is the difference in SST anomaly between the tropical western equatorial Indian Ocean (WEIO; 50°E - 70°E, 10°S -10°N) and the tropical south-eastern equatorial Indian Ocean (SEEIO; 90°E - 110°E, 10°S - Equator). This SST anomaly, which express the strength of IOD is known as Dipole Mode Index (DMI). IOD have two modes like La-Niña and El-Niño. They are positive IOD phase and negative IOD phase. Positive phase of IOD is characterized by cooling of SST in the south eastern equatorial Indian Ocean and experience anomalous warming of SST in Western equatorial Indian Ocean (Fig. 3a). A reversal condition occurs in the negative phase of IOD (Fig 3b). A positive phase of IOD pattern results in a decrease in rainfall over central and southern part of Australia. While a negative phase of IOD results in an increase of rainfall over central and southern part of Australia.

Ashok (2001) suggested that, whenever the ENSO - ISMR correlation is low (high), the IOD - ISMR correlation is high (low). The IOD plays an important role as a modulator of the Indian monsoon rainfall, and influences the correlation between the ISMR and ENSO. There is a strong association of the large anomalies in the Indian monsoon rainfall with the Equatorial Indian Ocean Oscillation (EQUINOO) and

ENSO. EQUINOO, along with ENSO, can explain all the seasons with large deficit or excess in the Indian monsoon rainfall during the satellite era (Gadgil, 2003).

Sarkar *et al.,* (2004) suggested that the effect of ENSO on Indian precipitation has not decreased but on the contrary it has increased on recent times. A stronger ENSO weakens the Walker circulation with the shifting of circulation cell to central Pacific and an overall low rainfall year ensures.

A large positive value of the IOD index represents a positive phase of IOD when SST is anomalously warm in the eastern Indian Ocean and cools the western Indian Ocean. The negative phase of IOD events characterize by anomalous warming of western tropical Indian Ocean, which triggers atmospheric convection and brings increased rainfall. A negative phase of IOD, in disparity, involves anomalously high SSTs in the eastern Indian Ocean and low SSTs in the west, bringing more rain to the western coast of Indian Ocean and less to the Eastern coast. The Indian Ocean dipole events are represented by the dipole mode index obtained by the SST anomaly difference over the western Indian Ocean and the southeast Indian Ocean (Ihara *et al.,* 2008).

2.8 Atmospheric stability, wind, cyclone and ET

The significance of Indian and Western Pacific warm pools and convective systems to monsoon processes has been much highlighted in the last 3-4 decades of monsoon research. With the withdrawal of south-west monsoon, the reversal of pressure and wind circulation, which take place at the commencement of October, a trough of low pressure zone becomes established in south BoB. The passage of westward moving low pressure waves occur which strengthens this trough. Depressions and cyclonic storms rarely form in the trough of low pressure over south BoB. This type of circumstances forces the equatorial oceanic air mass in appropriate depth to move in the direction of south India causing wide spread rainfall (Rao and Jagananathan, 1953).

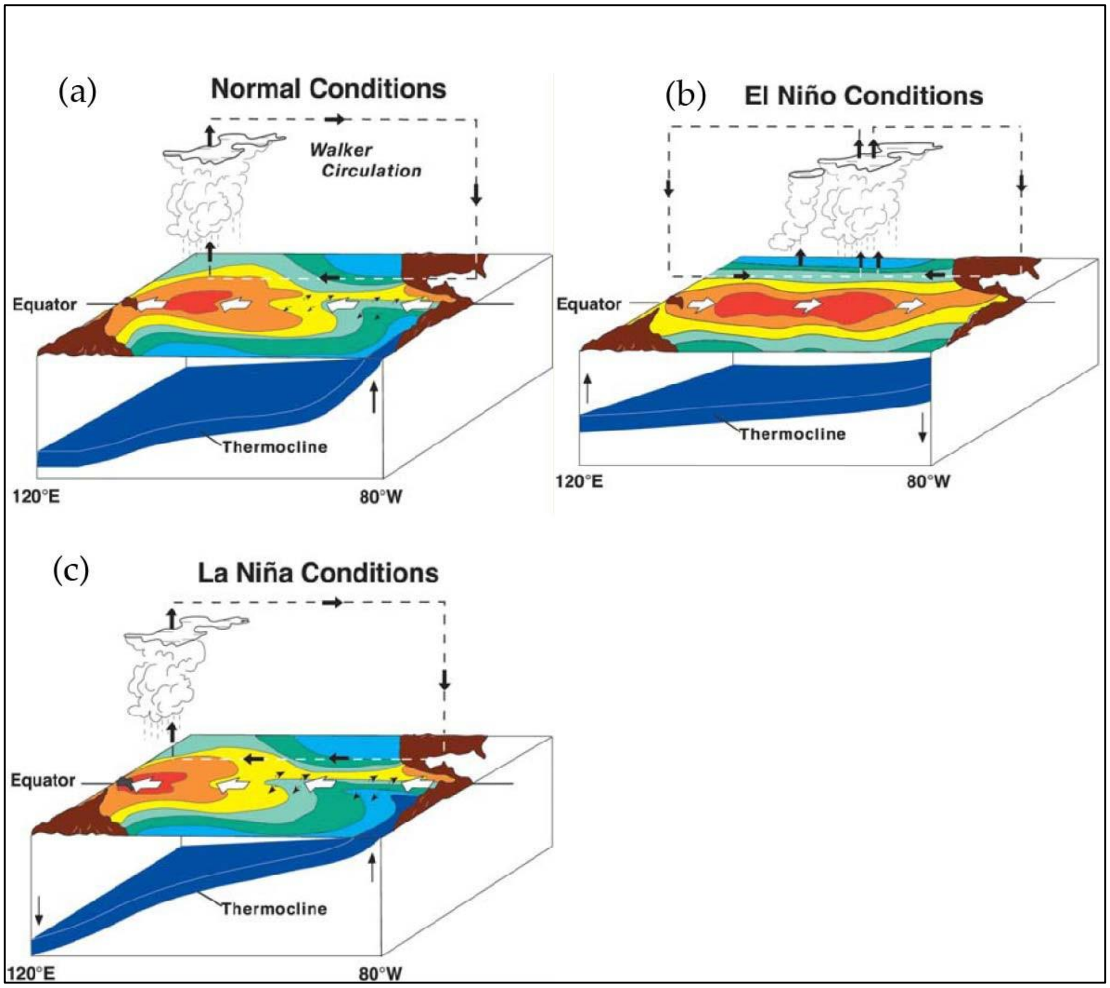

Figure 2. Schematic of (a) normal, (b) El-Niño and (c) La-Niña conditions in tropical Pacific. (Courtesy. *McPhaden, 2004*).

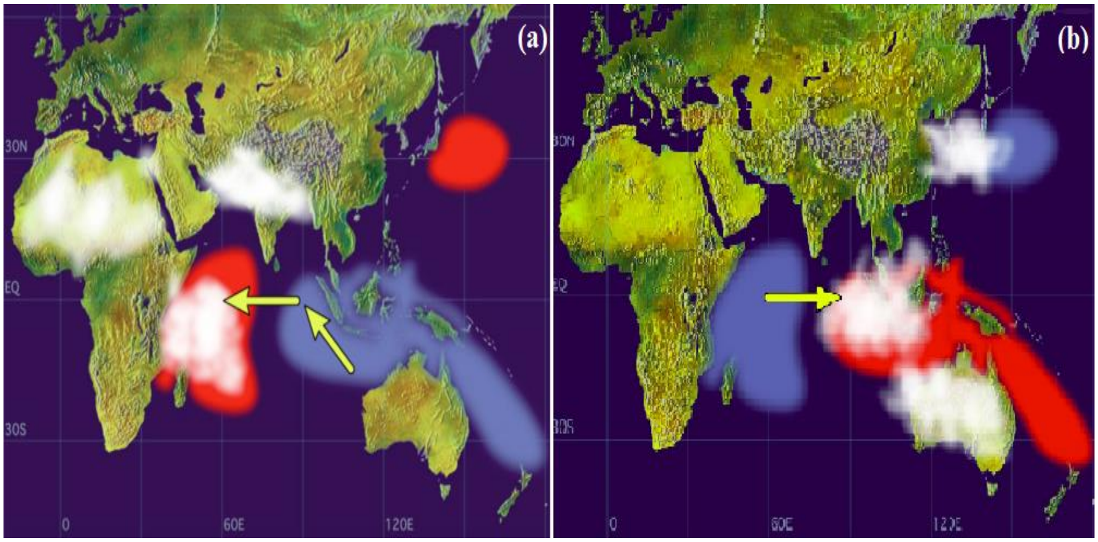

Figure 3. Schematic showing Indian Ocean Dipole events. Red shading denoting warming; blue cooling. White patches indicate increased convective activity with arrows indicating wind direction. (Image courtesy: *Institute for Global Change Research, Yokohama City, Japan*).

(a) A positive IOD event with marked positive SST anomaly in the western tropical Indian Ocean and a negative anomaly in the eastern tropical Indian Ocean.

(b) A negative IOD event with negative SST anomaly in the western tropical Indian Ocean and a positive SST anomaly in the eastern tropical Indian Ocean. . The negative IOD which is, in effect, the reversal of the positive IOD.

The frequency, intensity, life cycle and propagation characteristics of the monsoon disturbances determine the regional distribution of rainfall, higher number of lows means greater instability of the monsoon trough (Shukla, 1987).

Compilation of surface winds from ship reports since 1854 shows a number of long period variation, including a trend towards strengthening wind over the past three decades (Cardone, 1990).

Due to the favorable atmospheric and oceanic environments, 80 per cent of the cyclones are formed in the BoB. With an annual frequency of about five cyclones (Bhaskar *et al.,* 2001). The thermal contrast between land and ocean, SST and moisture are the crucial factors for its evolution and intensity. The lower tropospheric moist static energy and the vertical stability play an important role not only in determining regions of organized convection but also in their temporal variation during the season (Gadgil, 2003).

The low level monsoon jet (LLJ), one among the major components of the Indian summer monsoon circulation, originates from a high-pressure mass centered over the southern Indian Ocean (Mascarene High), crosses equator off east coast of Africa, turns right and flows across India which carries moisture from the Arabian Sea (AS) and pours heavy rainfall over this region during the summer monsoon season (Joseph and Sijikumar, 2004).

MATERIALS AND METHODS

CHAPTER 3

MATERIALS AND METHODS

3.1 Data Used

Data on SST, wind, precipitation, outgoing longwave radiation (OLR) and tropical cyclone were used for this study. The data description and time period is given below.

3.1.1 Sea Surface temperature (SST)

SST is a measure of the energy due to the motion of molecules at the top layer of the ocean. Sea surface temperature is a key climate and weather measurement obtained by satellite microwave, infrared (IR) radiometers, *insitu* moored buoys, drifting buoys, and ships of opportunity. In this study, Hadley Centre Global Sea Ice and SST (HadISST) dataset is used to observe the relative changes in SST for different selected areas. The extended reconstructed sea surface temperature (ERSST) used for checking the robustness of the result produced by HadISST.

3.1.1.1 HadISST

The SST data extracted for this study is from HadISST, established at the Met Office Hadley Centre for Climate Prediction and Research. The Hadley Centre Global Sea Ice and SST (HadISST) is a grouping of monthly globally complete fields of SST data for 1871-present.

HadISST uses reduced space optimal interpolation applied to SSTs from the Marine Data. The 'bucket correction' was applied to SSTs for 1871-1941. It utilize both *insitu* SSTs from ships and buoys and bias adjusted SSTs from the satellite-borne advanced very high resolution radiometer, following reduced space interpolation methods (Rayner *et al.,* 2003). SSTs were assigned a fixed value (-1.8°C) for areas with sea ice cover of greater than 90per cent. HadISST provides a unique, globally complete analysis of historical SST data on a 1°x1°, monthly grids since 1871. In the present study, SST data over 1950-2010 period is used.

3.1.1.2 ERSST

The Extended Reconstructed Sea Surface Temperature (ERSST) was assembled consuming the most freshly accessible International Comprehensive Ocean-Atmosphere Data Set (ICOADS) SST data and upgraded statistical methods that tolerate stable re-establishment using sparse data (Smith and Reynolds, 2003). The monthly analysis begins during January 1854, but because of sparse data the analyzed signal is heavily damped before 1880. Afterwards the signal strength become steadier over time. When new data become available, then ERSST will update.

Presently, the ERSST Version 3 and ERSST version 2 are available. ERSST version 2 is an improved extended reconstruction. In the reconstruction the high-frequency SST anomalies are reconstructed by fitting to a set of spatial modes. Compared to the earlier reconstruction, version 1, in the weak variance region better resolved in improved reconstruction. SST data over 1950-2010 period is used in this study for checking the robustness of the results produced using HadISST.

3.1.2 Wind

Wind data used for this study is in the level of 850 hpa. Because of strong winds approximately 1.5 km above sea level. Zonal and Meridional wind data downloaded from NCEP/NCAR for studying the direction of pressure variability and supporting the results.

3.1.2.1 NCEP/NCAR

The NCEP/NCAR reanalysis data set is a frequently bring up-to-date gridded data set on behalf of the state of the earth's atmosphere, combining Observation, interpretations and Numerical Weather Prediction model output from 1948 to the present. It is the joint project of National Centre for Environmental Prediction (NCEP) with the National Centre for Atmospheric Research (NCAR). This reanalysis project began in 1991 as an outgrowth of NCEP Climate Data Assimilation System (CDAS) project. The data observation and collection is performed by NCAR, the surface and upper air observations are being organized by reanalysis.

In the present study, monthly data of zonal and meridional wind with 2.5°x2.5° resolution has been used. The output variables are classified into four categories, depending on the relative influence of the observational data and the model on the gridded variable (Kalnay *et al*., 1996). The data downloaded from www.esrl.noaa.gov/psd/data/grided/.

3.1.3 Precipitation

The Indian Institute of Tropical Meteorology (IITM) precipitation data set is based on a denser network of rain gauges. This data set obtained from 306 uniformly widely distributed rain gauge stations. The data is available from the year 1871. The hilly regions consisting of four meteorological subdivisions of India which are parallel to Himalayan mountain range have not been considered in view of the meagre rain-gauge network and low areal representation of a rain-gauge in a hilly area. Two island subdivisions far away from mainland have also not been included. Thus, the contiguous area having network of 316 stations over 30 meteorological subdivisions measures about 2,880,000 km^2, which is about 90 per cent of the total area of the country.

Longest Instrumental Rainfall Series of the Indian Regions (1813-2006) is used from IITM data archival. Rainfall data used in the present study for different regions of the Indian subcontinent (Sontakke *et al.,* 2008). Longest possible instrumental area-averaged monthly, seasonal and annual precipitation series of seven homogeneous zones and the whole India have been developed using highly quality-controlled data from well spread network of 316 rain gauge stations.

The monthly rainfall data for the meteorological sub-divisions over the India have been downloaded from the website of the Indian Institute of Tropical Meteorology (IITM, www.tropmet. res.in). For the present study, regional rainfall data for southern peninsular India in October to December months from 1950 to 2010 is considered. The original station rainfall data required for the sub-divisional averages are obtained from the Indian Meteorological Department (IMD).

3.1.3.1 GPCP

The Global Precipitation Climatology Project (GPCP) (Adler *et al.,* 1997) data set of the Laboratory for Atmospheres at the National Aeronautical and Space Administration (NASA) Goddard Space Flight Center contains global precipitation data and was established by the World Climate Research Program. The GPCP datasets are established and updating with worldwide cooperation and are used by the global research community. One of the main aim of GPCP is to improve a more comprehensive understanding of the spatial and temporal patterns of global precipitation. Data from over 6,000 rain gauge stations, and satellite geostationary and low-orbit infrared, passive microwave, and sounding observations have been merged to estimate monthly rainfall on a 2.5^0 global grid from 1979 to the present. The combination of satellite-based rainfall estimates provides the most useful and complete analysis. Pentad precipitation data of GPCP is used for the present study and robustness of the result checked using TMI dataset. Data is available covering the region of geographic longitude: 0°E - 360°E, and geographic latitude: -90°N - 90°N. The data available from the website http://precip.gsfc.nasa.gov/.

3.1.3.2 TMI

The Tropical Rainfall Measuring Mission (TRMM) was launched November 27, 1997 carrying five instruments, one of which is the TRMM Microwave Imager (TMI). TMI is a multi-channel, dual polarized, conical scanning passive microwave radiometer designed to measure rain rates over a wide swath under the TRMM satellite. TRMM is a joint space mission between NASA and the Japan Aerospace Exploration Agency (JAXA) .It is designed to observe, monitor and study tropical rainfall. The term refers to the mission itself and the satellite which the satellite uses to collect data. TRMM is part of NASA's mission to Planet Earth, a long term coordinated research effort to study the Earth as a global system. The data sets are available only since 1998 with a resolution of 0.25°x 0.25°. TMI data provides rain rate, wind speed, columnar water vapor, cloud content, SST. TMI represents the first microwave spacecraft sensor capable of accurately measuring SST through clouds. Hence it is an optimal data product suitable for analysis. TMI data is used for checking the robustness of the result. The data downloaded from ftp://ftp.remss.com/tmi.

3.1.4 Outgoing longwave radiation

OLR (Outgoing Longwave Radiation) is the energy re-emitted by the Earth as infrared radiation at low energy and longer wavelength. It is a critical constituent of the Earth's radiation budget and represents the total radiation going to space emitted by the atmosphere. OLR and the convective activity is directly related. If OLR is less than there will be great convection occurs and vice-versa. The data used in the study is taken from NCEP/National Oceanic and Atmospheric Administration (NOAA) Climate Diagnostics Center (Liebmann and Smith, 1996). The six hourly data is taken and averaged to daily mean value of OLR for the cyclone period.

3.1.5 Tropical cyclone

The cyclone track data in AS, BoB and North West Pacific (NWP) from 1979 to the percent is from UNISYS (http://weather.unisys.com/hurricane). The chart color codes intensity used in provided tracks of cyclone by UNISIS hurricane is used based on Saffir-Simpson scale (Appendix-I). The criteria used in the classification of cyclonic storm and severe cyclonic storm are as follows: depression– maximum sustained wind between 18 and 33 knots; cyclonic storm–maximum sustained wind between 34 and 47 knots; severe cyclonic storm–maximum sustained wind of 48 knots or more. The track data of cyclone is available from weather.unisys.com/hurricane/.

3.2 Softwares and programming languages

Different programming languages and software were used for proceeding the study and generating the figures. The programming languages used are C++ and FORTRAN. The softwares used are GrADS, FERRET and GMT. The description about the languages and softwares are given below.

3.2.1 FORTRAN programming Language

FORTRAN (FORmula TRANslation) is a third generation programming language for the general use of mathematical and scientific computation. FORTRAN programming language is used in this study for calculating the density of tropical cyclone passing through every $1^0 * 1^0$ grid boxes in the North West Pacific area. The robustness of the result checked using C++ programming Language. Fortran 95 have so many new facility than the older FORTRAN versions.

Nested where and if facilitate for counting the number of cyclone passing to every grid points. Default initialization to derived type components include pointer initialization. In do statement double and real type variables can also use in this version. End If statement blocks the complete nested If statements. Fortran 95 also include two optional modules they are varying character strings and conditional compilation. The data made by this language further converted to pictorial representation by generic mapping tool (GMT).

3.2.2 C++ programming Language

C++ is an object oriented middle level programming language. C++ language is used in this study for checking the robustness of the data generated by FORTRAN languages.

3.2.3 GrADS

The Grid Analysis and Display System (GrADS) is an interactive desktop tool that is used for easy access, manipulation, and visualization of earth science data. GrADS uses a 5-Dimensional data environment: the four conventional dimensions (longitude, latitude, vertical level, and time) plus an optional 5^{th} dimension for grids that is generally implemented but designed to be used for ensembles. Data sets are placed within the 5-D space by use of a data descriptor file.

GrADS handles grids that are regular, non-linearly spaced, gaussian, or of variable resolution. Data from different data sets may be graphically overlaid, with correct spatial and time registration. Operations are executed interactively by entering FORTRAN-like expressions at the command line. A rich set of built-in functions are provided, but users may also add their own functions as external routines written in any programming language. GrADS has a programmable interface (scripting language) that allows for sophisticated analysis and display applications. Use scripts to display buttons and drop menus as well as graphics, and then take action based on user point-and-clicks. GrADS software is used to generate different figures in the present study.

3.2.4 FERRET

Ferret is an interactive computer visualization and analysis environment designed to meet the needs of oceanographers and meteorologists analyzing large and complex gridded data sets. "Gridded data sets" in the Ferret environment may be multi-dimensional model outputs, gridded data products (e.g., climatology), singly dimensioned arrays such as time series and profiles, and for certain classes of analysis, scattered n-tuples (optionally, grid-able using Ferret's objective analysis procedures). Ferret's gridded variables can be one to four dimensions—usually (but not necessarily) longitude, latitude, depth, and time. Ferret is used in this study for checking the result that generated by GrADS.

3.2.5 GMT

GMT (Generic Mapping Tool) is an open source collection of about 80 command-line tools for manipulating geographic and Cartesian data sets (including filtering, trend fitting, gridding, projecting, etc.) and producing PostScript illustrations ranging from simple x–y plots via contour maps to artificially illuminated surfaces and 3D perspective views. All of the figures showing study area is generated by using GMT software. Cyclone track and density also generated with this software using the dataset produced by FORTRAN programming language.

3.3 Study Area

Equatorial Trough (ET) regions in the Indian Ocean and Bay of Bengal (BoB) regions are used in this study. ET regions defined as the area bounded between the equator to 10°S latitude and between the longitudes 60°E - 110°E in this study. The equatorial trough was further divided into four overlapping regions, ET-II (70°E - 90°E; 0°- 10°S), ET-III (80°E - 100°E; 0° - 10°S) and ET-IV (90°E - 110°E; 0° - 10°S). In order to look into the variability of convection over the ET, Outgoing Longwave Radiation (OLR) and 850 hpa wind vector have been studied. The convection over BoB region was also studied for supporting the results. The various equatorial and Indian Ocean regions used in the study is depicted in Fig.4.

To understand the concurrent relationship of SST over different Indo-Pacific regions, SOI and WCI on the monsoon activity over the Indian subcontinent five regions were selected. Region-I (80°W - 20°W, 10°S - 10°N), Region-II (180°E - 140°W, 10°S - 10°N), Region-III (120°E - 160°E, 10°S - 10°N), Region-IV (120°E -

160°E, 10°S - 10°N), Region-V (50°E - 70°E, 10°S - 10°N) in the Indian and Pacific Ocean depicted in Fig. 5. Sea surface temperature over this region was studied for analyzing the changes. The SST anomaly studied in the western equatorial Pacific (WEP {From here onwards WP in the Fig. 15. is known as WEP}; 120°E - 130°E, 5°S - 5°N) region and eastern equatorial Pacific (EEP {From here onwards EP in the Fig. 15. is known as EEP}; 80°W-90°W, 5°S- 5°N) region. The difference of this SST anomaly between WEP and EEP taken as an index of the intensity of Walker Circulation (WCI), with positive (negative) WCI leading to stronger(weaker) Walker circulation. The Southern Oscillation Index (SOI) has been extracted from the NOAA website. Monthly mean SST has been extracted from HadISST data. SST data over the five regions (Region 1 to 5 as depicted in the Fig. 5.) is used in the present study. Rainfall data used for different regions of the Indian subcontinent is take out from IITM website. The homogeneous macro regions used in the study is depicted in Fig. 6. Macro regional and all India rainfall dataset (Sontakke *et al.,* 2008) were used in the different sections of analysis. The trend analysis of Niño regions is highlighted in the study and the Niño regions are Niño 4 (160°E - 150°W, 5°S - 5°N), Niño 3.4 (170°W - 120°W, 5°S - 5°N), Niño 3 (150°W - 90°W, 5°S - 5°N) and Niño 1+2 (90°W - 80°W, 10°S - 0°) are depicted in Fig. 7.

3.4 Methodology

Present study focused on the active and break monsoon period of the Indian summer monsoon activity. The role of convective activity over the ET regions with the monsoon activity (number of break/active days and their frequency) was examined. The partial correlation between regional rainfall with SST, outgoing long wave radiation (OLR), Break days and number of convective systems (NWP and NIO) was worked out. There was no significant correlation between BoB cyclones and ET regional rainfall whereas the NWP cyclones are significantly correlated. Hence further studies concentrated on cyclones in NWP. Ten years, five with

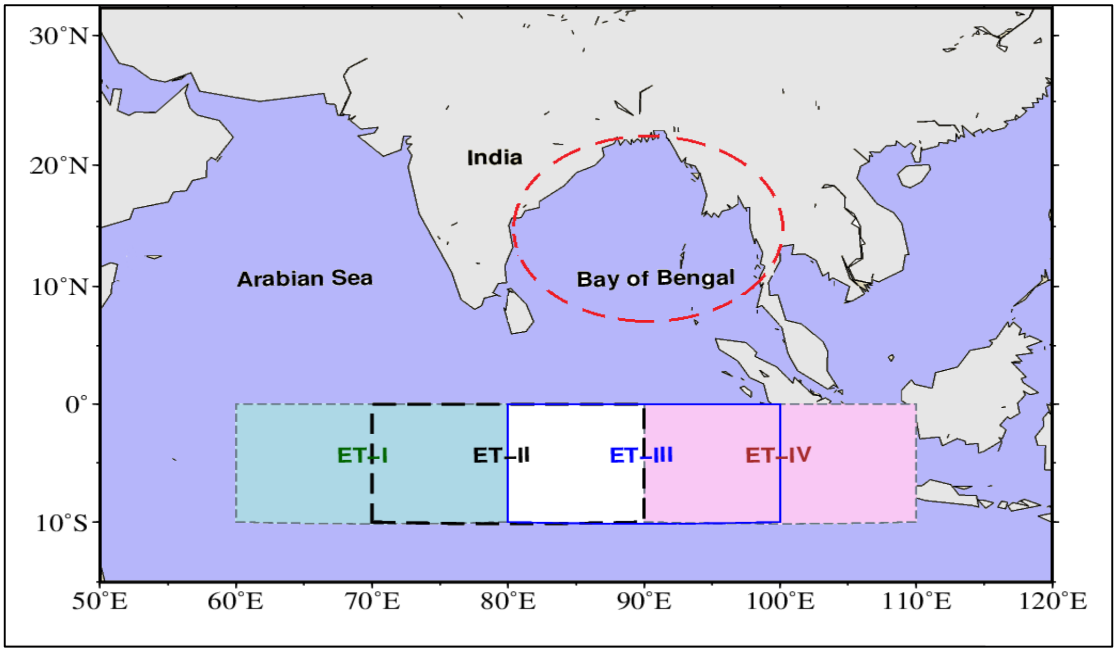

Figure 4. Study areas used in the Indian Ocean regions to understand the convective activity during 1979-2010.

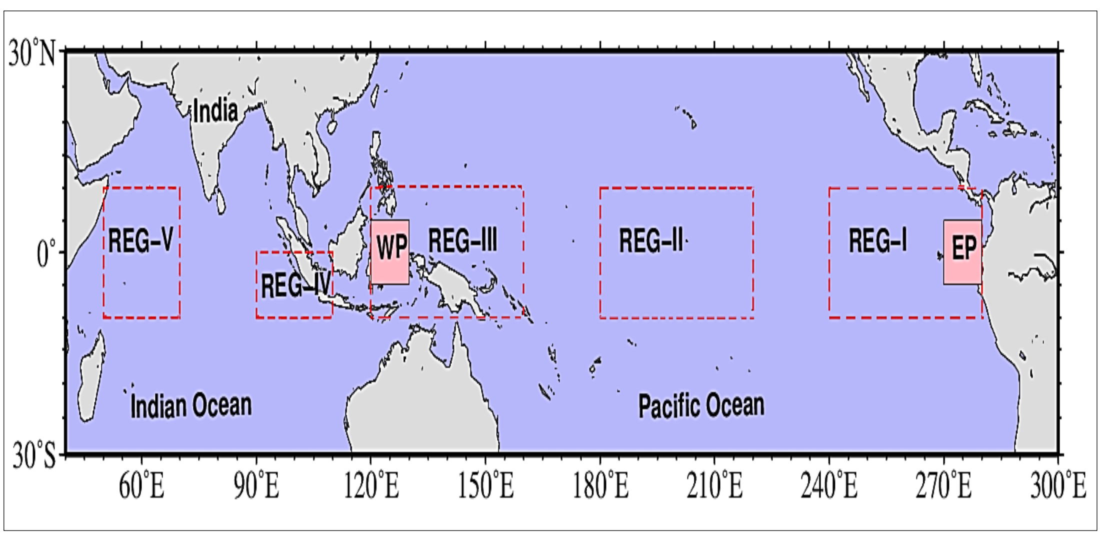

Figure 5: Study area used in the Indo Pacific regions to understand the concurrent relationship of SST.

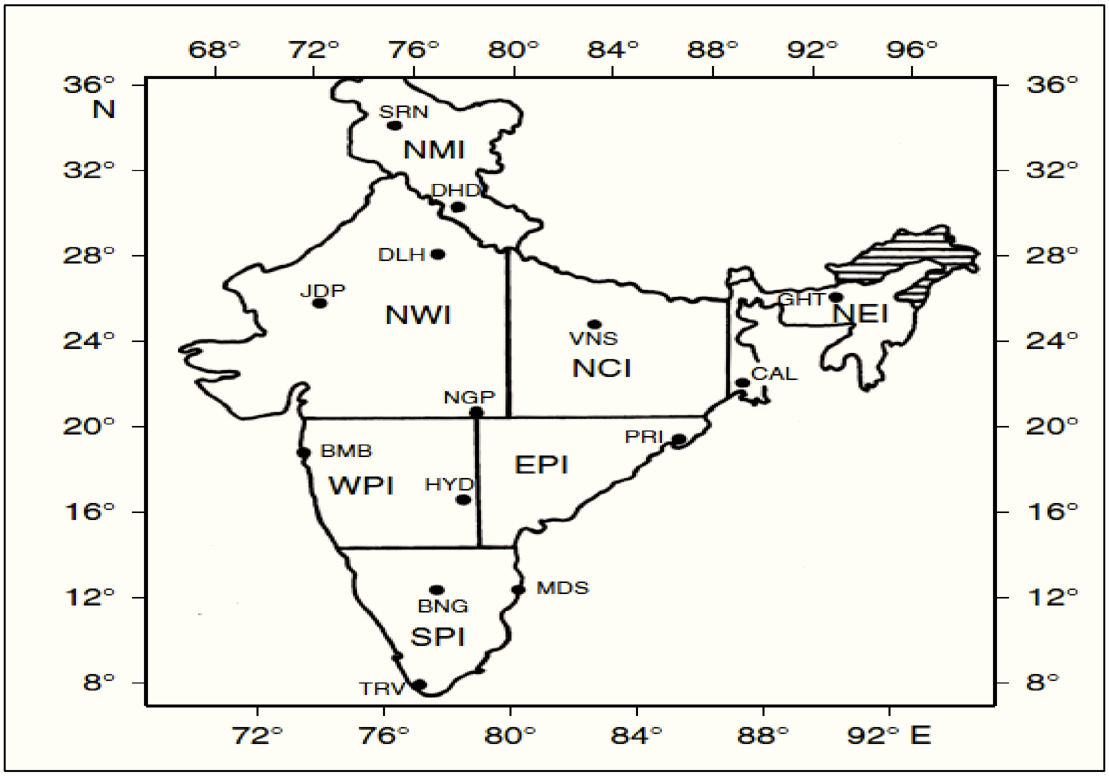

Figure 6. The homogeneous Indian region used in the study (Reproduced from Sontakke *et al.,* 2008).

SPI – Southern peninsular India.

EPI - Eastern peninsular India.

WPI- Western peninsular India.

NEI- North east India

NCI- North central India

NWI- North west India

NMI – North mountainous India

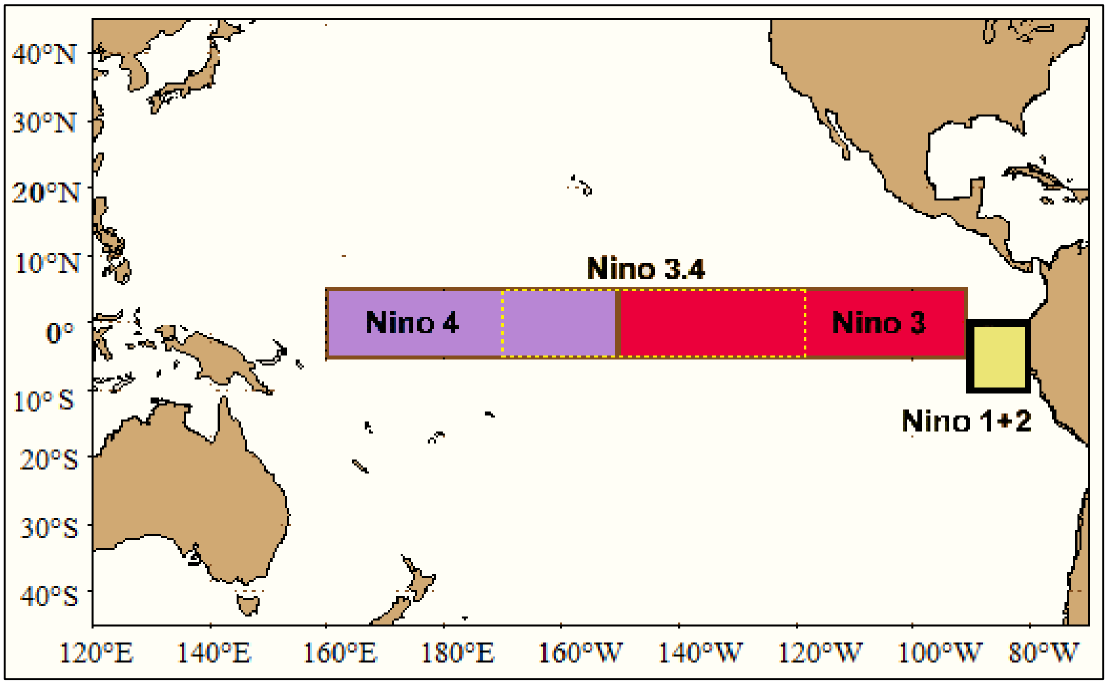

Figure 7. Niño regions used in the study.

prolonged active spells and another five with prolonged break spells were selected. In the present study OLR is used as a proxy for convection. Convective activity over the ET and BoB region studied using OLR and 850 hpa level wind data. Present study further focused on the relative roles of convective activity in the NWP and ET on the Indian summer monsoon activity. Cyclonic density, composite cyclonic track and selected year wise cyclonic tracks plotted over NWP region and studied accordingly with the number and direction of cyclonic storms. Mean position of cyclonic storm was plotted for better understanding.

SST anomaly was used, to study the difference between WEP and EEP as an index of the intensity of Walker circulation (WCI), with larger SST difference leading to stronger Walker circulation. The SOI used in the present study was extracted from NOAA website. The SST data over five regions (Fig. 5.) were used for studying the concurrent relationship of SST over Indo-Pacific region. Decadal analysis (1950-2010) carried out for studying the spatial changes of SST. Decadal difference was calculated and studied the increase/decrease in SST from 1950 to 2010. Temporal plot of Indian monsoon rainfall, WCI and SOI analyzed with respect to El-Niño and La-Niña condition. WCI is correlated finely with increase/decrease in Indian summer monsoon rainfall. Different Niño regional SST, DMI, WCI and SOI plotted for studying the trend.

3.4.1 Break (Active) in monsoon conditions

Rajeevan *et al.* (2010) have proposed new technique to describe active and break spells in summer monsoon. This criteria was used in this study to define active and break spells. They considered July and August for active and break spells, the normalized anomaly of the rainfall over the monsoon core zone exceeds 1 or is less than −1.0 respectively, this criterion is satisfied for at least three consecutive days. Table 2 and 3 gives the details of various break (active) period and number of break (active) days for the study period. The break (active) conditions for the months of July and

August were used. For the reason that a delayed onset or early withdrawal can create artificial breaks during June or September (Ramesh and Uma, 2004).

The study was conducted for five years with great prolonged active days during 1982 (17-23 August), 1994 (9-17 July), 1995(18-25 July), 1997 (20-26August) and 2006 (13-22 August). Another five years with longest prolonged break days during 1979 (14-29 August), 1986 (22-31 August), 2000 (01-09 August), 2002 (04-17 August) and 2009 (29July-10August) for observing the position of convection and wind field over the region. The break days and active days were extracted from Rajeevan *et al.* (2010), and it is given in Appendix-II and III. The terminology break monsoon or active monsoon years were used to indicate the five longest prolonged break or active years. In the present study most of the selected years have one or two monsoon breaks, but only one longest prolonged break were used for this study.

3.4.2 Correlation coefficient and statistical significance

Correlation coefficients measure the strength of association between two variables. The most common correlation coefficient, called the Pearson product-moment correlation coefficient, measures the strength of the linear association between variables. In this study Pearson correlation coefficient was used.

The correlation ρ between two variables is:

$$\rho = [1 / N] * \Sigma \{[(Xi - \mu X) / \sigma x] * [(Yi - \mu Y) / \sigma y]\}$$

Where

N is the number of observations in the population,

Σ is the summation symbol, Xi is the X value for observation i,

μX is the population mean for variable X,

Yi is the Y value for observation i,

μY is the population mean for variable Y,

σx is the population standard deviation of X, and

σy is the population standard deviation of Y.

Statistical significance (Appendix-IV) was ascertained to determine the reliability of data.

RESULTS AND DISCUSSIONS

CHAPTER 4

RESULTS AND DISCUSSIONS

The results of the present study and the discussions on the results are presented below

4.1 Relative role of convection over ET and cyclones in NWP on Indian summer monsoon activity

The summer monsoon which gives about 80 per cent of the mean annual rainfall for the various meteorological subcontinents is one of outstanding meteorological phenomena of the Indian meteorology (Ananthakrishnan and Pathan, 1981). The existence or nonexistence of break and active cycle of precipitation over the Indian subcontinent during the summer monsoon central months of July and August decides destiny of monsoon rainfall. Many scientists have used different parameters as a proxy for the convective activity over the Equatorial Indian Ocean such as SST, Cloudiness, OLR, satellite estimated rainfall and low level wind flow at 850 hpa. Present study is an attempt to understand the relative role of convection over ET as well as convective systems over NWP and North Indian Ocean (NIO) on Indian summer monsoon.

4.1.1 Sea surface temperature

SST scattered diagram prepared for July and August during 1979-2010 for the four selected ET regions are showed in Fig. 8. The trend estimated value was higher at ET-II (0.5745) followed by ET-III (0.4782), ET-I (0.4586) and ET-IV (0.1161). SST variations in recent decades are mainly due to differential heating of land and ocean. Roxy (2013) suggested that during 1901–2012, the western Indian Ocean experienced anomalous warming of 1.2°C in summer SSTs while the Indian Ocean warm pool went through an increase of 0.7°C. The warming of the generally cool western Indian Ocean against the rest of the tropical warm pool region alters the zonal SST gradients, and has the potential to change the Asian monsoon circulation and rainfall. According to Roxy *et al.* (2014), Indian Ocean has been warming consistently for over century and at a faster rate than any other region of Tropical Ocean, and this may weaken the Indian monsoon circulation. Indian Ocean SST plays an important role in the variation of the global climate, because the absolute value of the SST high over the Indian Ocean, even small change in the Indian Ocean SST can produce significant impacts on global climate (Yanh Zhou *et al.,* 2014).

4.1.2 Outgoing longwave radiation

OLR scattered diagram prepared for July and August during 1979-2010 for the four selected ET regions are presented in Fig. 9. The trend estimated value for ET-III was higher (0.3627) followed by ET-IV (0.3542), ET-II (0.2462) and ET-I (0.00006).

According to Meehl (1987), the seasonal movement of the rainfall coincides with the movement of the convective zones observed in the OLR indicated by the satellite imagery of reflectivity.

4.1.3 Rainfall

Rainfall scattered diagram prepared for July and August during 1979-2010 for the four selected ET regions are represented in Fig. 10. The trend estimated value for ET-II was higher (0.2194) followed by ET-I (0.2042), ET-III (0.1506) and ET-IV (0.0245). The GPCP data is better suited for looking at the oceanic precipitation than the CMAP merged Gauge satellite monthly precipitation estimates (Yin et al., 2004).The CMAP precipitation was showing a decreasing trend in oceanic precipitation, which could be due to an artefact of the input data change and atoll sampling error.

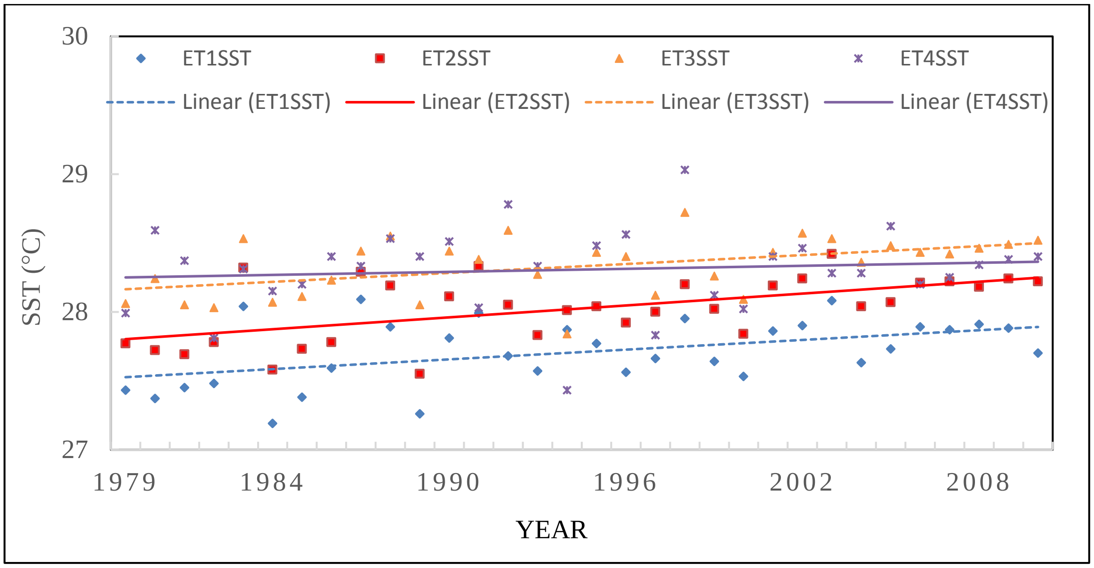

Figure 8. Comparison of SST from four selected ET regions during 1979-2010.

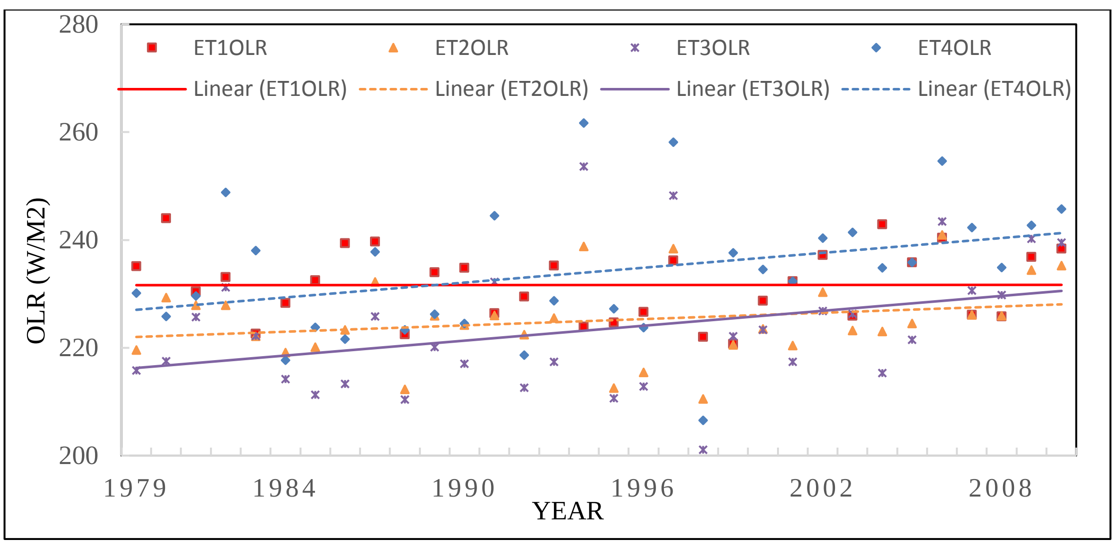

Figure 9. Comparison of OLR from four selected ET regions during 1979-2010.

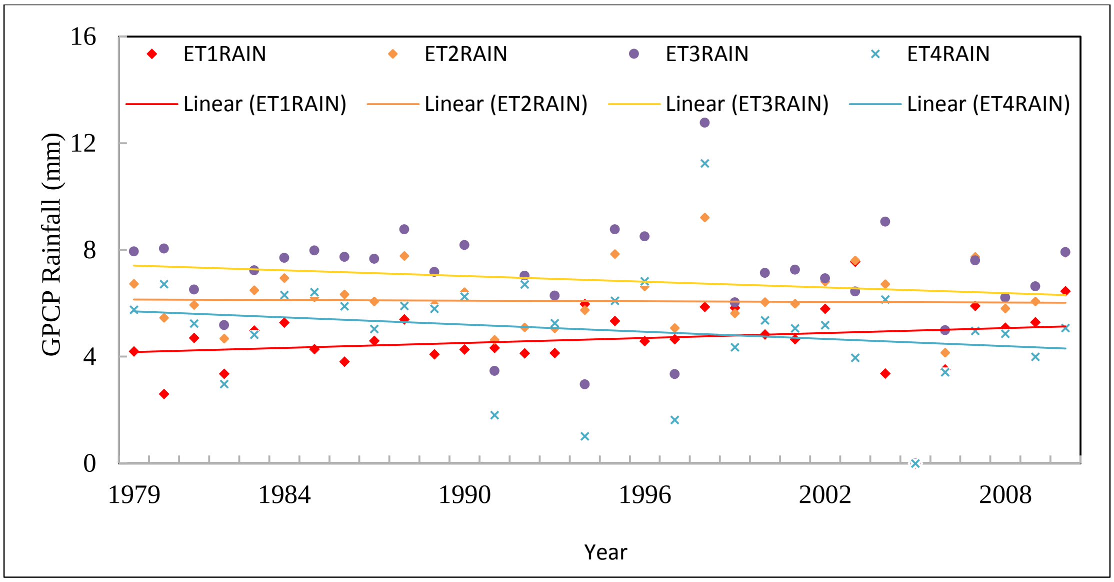

Figure 10. Comparison of GPCP rainfall from four selected ET regions during 1979-2010.

4.1.4 Equatorial trough and Indian monsoon

The correlation between the convection and sea surface temperature, outgoing longwave radiation, break days and number of convective systems in northwest Pacific over ET regions during July- August are given in Table 1. The superscript values for 1,2,3,4 and 5 represent the statistical significant level of 0.10, 0.05, 0.02, 0.01 and 0.001. The correlation between convection and SST was higher at ET-IV (0.85) followed by ET-I (0.52), ET-III (0.50) and ET-II (0.24). The regions ET-II (0.52), ET-III (0.50) and ET-IV (0.37) are negatively and significantly correlated with the NWP convective systems. There was a see saw in convection between the NWP system and convective activity over ET-III (0.50) region. SST, OLR and NWP convective systems showed the maximum correlation with rainfall in the selected regions. But there was no significant correlation existed with the north Indian Ocean cyclonic systems and rainfall over other regions. The driving forces of the BoB cyclones are achieved from the cyclonic vorticity of NWP. The selected regions are very near to NIO but the effect of NIO cyclones are very less there.

The Indian monsoon is now understood to be an integral part of the global climate system involving coupled atmosphere-land-ocean interactions (Webster *et al.,* 1998).The cyclone in the northwest Pacific also important when considering the monsoon rainfall over India. Sixty per cent of the tropical cyclone in the northwest Pacific occurred during summer monsoon season. The depressions and lows form over the north of BoB is influenced by the formation of cyclone in the west Pacific. This cyclone triggers the BoB cyclones in some extend. The distribution of Indian monsoon rainfall is influenced by tropical cyclone in west Pacific Ocean (Vinay and Krishnan, 2005).

Table 1. Correlation coefficients & statistical significance in the simultaneous regions during 1979-2010.

Regional rainfall	SST	OLR	Break days	NIO convective systems	West Pacific convective systems
ET -I	0.52^{4}	0.06	0.02	0.14	0.12
ET -II	0.24	0.10	0.16	0.12	0.52^{4}
ET -III	0.50^{4}	0.30^{1}	0.24	0.00	0.50^{4}
ET -IV	0.85^{5}	0.33^{1}	0.22	0.04	0.37^{2}

1=> 90%; 2=>95%; 3=>98%; 4=>99%; 5=>99.9%

4.1.5 Convective activity in the tropical Indian Ocean

A ten year period in recent decades was selected to understand the convective activity during active and break monsoon period. The break /active days are extracted from Rajeevan *et al.* (2010), it is given in Appendix II and III (the terminology break /active monsoon years are used to indicate five longest prolonged break /active years).

The convective activity during prolonged active days is shown in Fig. 11a. During 1982, the active convection was observed over BoB, but there was no convection over AS and ET regions. In 1994, wind over the Indian subcontinent was favorable for an active monsoon condition. The active convection and dominant southwesterlies was noticed over eastern AS and BoB during 1995. The convection was perceived over the eastern BoB region during the prolonged active days of 1997. During 2006 the convection was located over BoB region while the convection over AS and ET was insignificant. The convective activities during prolonged break days are presented in Fig. 11b. During 1979 and 1986, strong convection was observed over ET regions. The unfavorable southwesterlies leads a break monsoon condition over the Indian subcontinent. The maximum convection occurred over eastern BoB and eastern ET regions was during 2000 and 2002. In 2009, ET regions were active to some extent but OLR showed low values over eastern BoB.

Relation between active and break spells with ISMR during the observation period is depicted in Table 2. The minimum value of ISMR observed during 1982 and it was 788.4 mm where the prolonged active and break days were 7 and 8 respectively. In 1994, the prolonged active days were 9 without any break days which leads to maximum value of ISMR (1020.7). Both the ISMR and prolonged active/break days were similar during 1995 and 1997. The prolonged active days (10) without any break days were observed during 2006. Relation between break spells with ISMR during 1979 showed maximum number prolonged active and break days were 4 and 17 respectively (Table 3). In 1986, number of prolonged break days (10) was less than that of 1979 leads an increase in total rainfall. The maximum ISMR occurred during 2000

(856.4mm). Both the 2002 and 2009 year had similar number of prolonged break days and the ISMR values were 715.5 and 698 respectively.

If OLR is less (towards blue colour), then the convective activity, increasing in that region. So there will be a low pressure region develops and all the wind from surrounding high will move to that region with copious amount of rainfall. The outgoing long wave radiation is a proxy indicator of convection and is may lead to precipitation when goes smaller range (200 Wm^{-2} or less), its lower value indicates wet areas and higher values indicate dry area over the globe (Vijay, 2014).

Goswami *et al.* (2006) demonstrated that the frequency and intensity of extreme rainfall events throughout the summer monsoon season have increased over the central India since the middle of the twentieth century while the low and moderate rainfall events have considerably decreased.

Krishnan *et al.* (2000) define break days as days with positive OLR anomalies over northwest and central India (i.e., only over the western part of the monsoon zone), provided the average OLR anomaly over $73^0 – 82^0$E, $18^0 – 28^0$N exceeds $10Wm^{-2}$.

Active and break spells of Indian monsoon condition is influenced by fluctuations in tropical convergence zones. Our present study showed that during break (active) monsoon conditions, the convection was more (less) over the Equator (BoB). An increase in the number of convective systems in west pacific shows highly negative correlation with equatorial trough activity. When the convection over Bay of Bengal pulls the monsoon current (low level flow) into peninsular India leads to active monsoon condition (Fig. 11a.) over the Indian subcontinent. When the convection shifts to eastern equatorial trough region, the monsoon current (low level flow) avoids the Indian subcontinent and creates break monsoon condition (Fig. 11b.) (Ramesh *et al.,* 2005).

In the Fig. 11, the strongest equatorial trough activity was seen in the year of 1979, followed by 1986 and 2009. Those years come under the category of prolonged break years. The strongest convection over BoB could be seen in the years of 1995, 1994 and 1997. There are many reasons influencing the convective activity and the destiny of Indian summer monsoon, one of the reasons is equatorial trough activity.

4.1.6 Convective systems over North West Pacific (NWP)

The convective systems during active monsoon years are depicted in Fig. 12a. The number of convective systems over South China Sea were very less during 1982. In 1994, the increased number of cyclones were dissipated towards the coast. While during 1995, the cyclone is distributed widely but most of them join in South China Sea. In 1995, the number of cyclones were very less and found to be widespread over the region. The number of cyclones were high, long duration and widely distributed during 1997 and 2006. The convective activity during break monsoon period is shown in Fig. 12b. The cyclones were long lasting and widely distributed during 1979 and 1986. The number of cyclones were high in 2000 and 2002. During 2009, number of cyclones were low and widely distributed.

Maximum number of cyclones during the prolonged active years were located near the South China Sea (Fig. 12a). Cyclones in the NWP are the main driving force of depression in the BoB. During prolonged break monsoon years, formation and dissipation of most of the cyclones are away from the South China Sea (Fig. 12b). The prolonged break monsoon years are characterised by more number of short period cyclones in the NWP than prolonged active years.

The co-occurrence of active/break spells and convective activity have considerable influence on ISMR. During an active spell, enhanced convection was observed over NIO while during break spell it was over ET regions. In 1994 and 2006, four active spells observed without any break spells. The maximum rainfall occurred during 1994 was due to the enhanced convection over BoB. The prolonged active/break spells were similar during 1982 showed minimum amount of rainfall over Indian subcontinent (Table 2). During the prolonged break year 2000, maximum ISMR was due to the combined effect of slightly active equatorial and strong cyclonic activity over NWP. More break days without any active days and strong cyclonic activity towards the coast in the NWP showed maximum ISMR during 2002 than 2009.

According to Sengupta and Ravichandran (2001), the active phase of the monsoon is marked by high surface wind and deep atmospheric convection. The buoy data show that sea surface temperature (SST) in the Bay of Bengal warm pool rises and falls with periods of weeks.

The number of tropical cyclones forming in the northwest and west – central Pacific is about 1.33 times higher during weak monsoon years compared to strong monsoon years. Secondly, there is a greater tendency for the tropical Pacific cyclones to recurve and move north ward (north of 20°N) during weak monsoon years relative to strong monsoon years (Vinay and Krishnan, 2005).

4.1.7 Convective systems over NWP and active/break period

The comparisons of cyclone density in the west Pacific region during the prolonged active monsoon years and break monsoon years are represented in Fig. 13a and Fig. 13b. Cyclones in the mid-monsoon months of the five active monsoon years and five prolonged break monsoon years depicts the large variability in the convective activity occurs during different monsoon years.

During the active monsoon years, the intensity of cyclone density was found to be high and are concentrated between 10° - 25° and 110° - 140° E region, whereas the cyclone density was less and widespread over the region during the break monsoon years. However the number of cyclones during the break monsoon years were high compared to that of active monsoon years in agreement with the previous studies (Vinay and Krishnan, 2005; Ramesh *et al.,* 2009a). The westward cyclones in the NWP is one of the driving force of convection over BoB and there by good amount of rainfall in India. The eastward cyclones in NWP will experience a break in the summer monsoon activity over the Indian subcontinent.

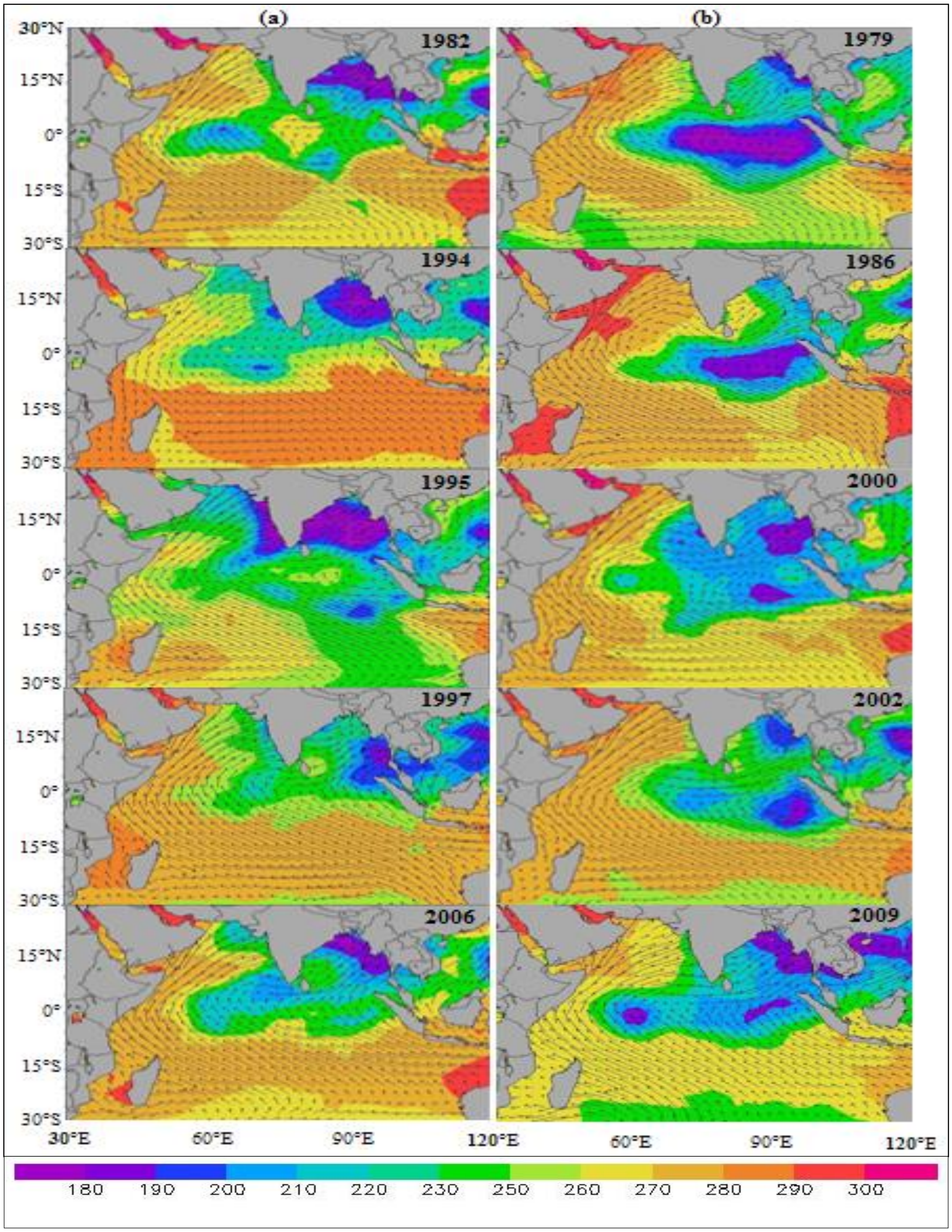

Figure 11. OLR and low level wind flow at 850 hpa during (a) prolonged active monsoon years (b) prolonged break monsoon years

Table 2. Relation between active/break spells with ISMR during the prolonged active monsoon years

Year	Active Spells	Break Spells	Prolonged active days	Prolonged break days	ISMR
1982	12–14A, 17–23A	1–8J	7	8	788.4
1994	2–4J, 9–17J, 18–20A, 25–27A	--	9	0	1020.7
1995	18–25J	3–7J, 11–16A	8	6	913.7
1997	30J–1A, 20–26A	11–15J, 9–14A	7	6	916.4
2006	3–6J, 28J–2A, 5–7A, 13–22A	--	10	0	927.8

Table 3. Relation between active/break spells with ISMR during the prolonged break monsoon years

Year	Active Spells	Break Spells	Prolonged active days	Prolonged break days	ISMR
1979	3–5A , 7–12A	2–6J , 14–29A	5	17	723.2
1986	21–24J, 13–15A	22–31A	4	10	779.7
2000	12–15J, 17–20J	1–9A	4	9	856.4
2002	--	4–17J, 21–31J	0	14	715.5
2009	13-16J, 21-23J	29J-10A, 17-19A	4	13	698.2

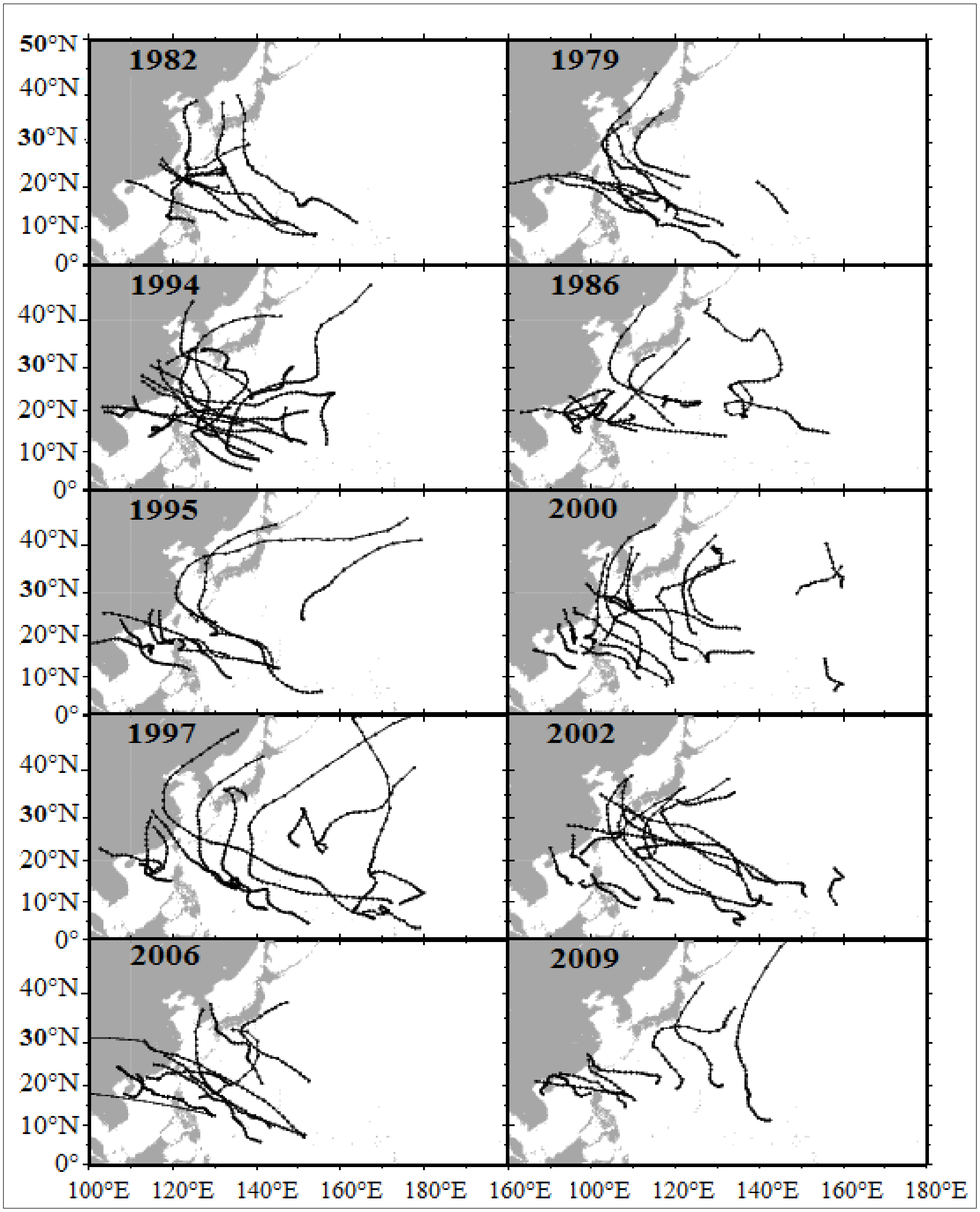

Figure 12. The cyclone track of year wise is given in figure (a) the tracks of cyclones in the mid monsoon months of prolonged active years and (b) the tracks of cyclones in the mid monsoon months of prolonged break years.

The significance of Indian, Western Pacific warm pools and convective systems to monsoon processes has been much highlighted in the last 3-4 decades of monsoon research. With the withdrawal of south-west monsoon, the reversal of pressure and wind circulation which take place in the commencement of October, a trough of low pressure zone becomes established in south BoB. The passage of westward moving low pressure waves occur which strengthens this trough. Depressions and cyclonic storms rarely form in the trough of low pressure over south BoB. This type of circumstances forces the equatorial oceanic air mass in appropriate depth to move in the direction of south India causing wide spread rainfall (Rao and Jagananathan, 1953) .

The composite tracks of cyclones in the NWP during the active/break monsoon years are represented in Fig. 14a and Fig. 14b. The number of cyclone observed during prolonged break years are quite higher than that of active years (Fig. 14a and Fig.14b.), and the occurrence is also very different. During the active years, cyclones were in the westward direction and dissipated between 10° - 25° and 110° - 140° E, which promotes convection over the BoB regions. The enhanced convection over this region regulates the monsoon activity over the Indian subcontinent. But during the break years, cyclones over the NWP regions were widespread and the intensity was less between 10° - 25° and 110° - 140° E.

During active monsoon years, more cyclones (blue dots) are located between 10° - 25° and 110° - 140° E (Fig. 15). But the cyclones (red dots) in the prolonged break monsoon years are widespread compared to that of active monsoon years. According to Ramesh et al. (2009b), it was found that in the deficit years and prolonged breaks in monsoon conditions, the systems (about 69 per cent) formed further south than in the case of excess monsoon years, the maximum difference in the shift of latitude and longitude was observed in the peak monsoon month of July indicating the significant influence of the convective systems over the northwest Pacific Ocean on the monsoon activity over the Indian subcontinent.

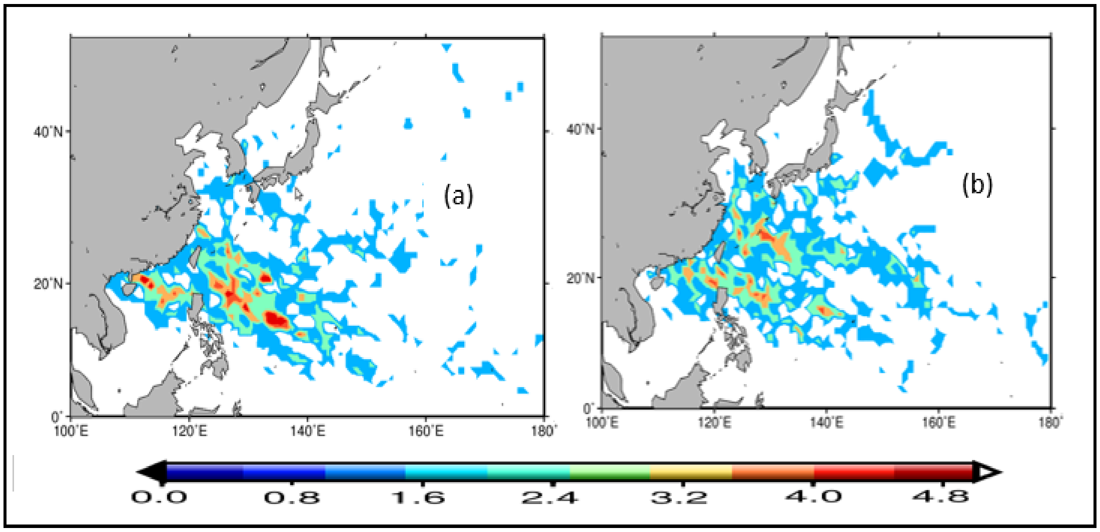

Figure 13. Cyclone density computed for 1°* 1° grid boxes by counting the number of cyclone passes through every grid boxes. Computed from mid-monsoon months for (a) five prolonged active monsoon years (1982,1994,1995,1997,2006) and (b) five prolonged break monsoon years (1979,1986,2000,2002,2009)

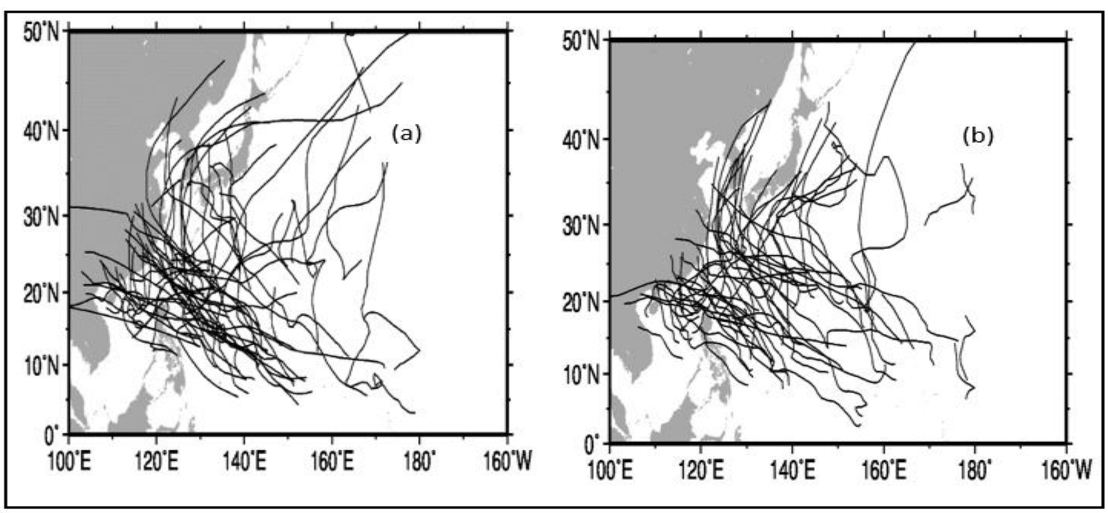

Figure 14. Composite tracks of cyclones in the NWP (a) during active monsoon years and (b) during break monsoon years.

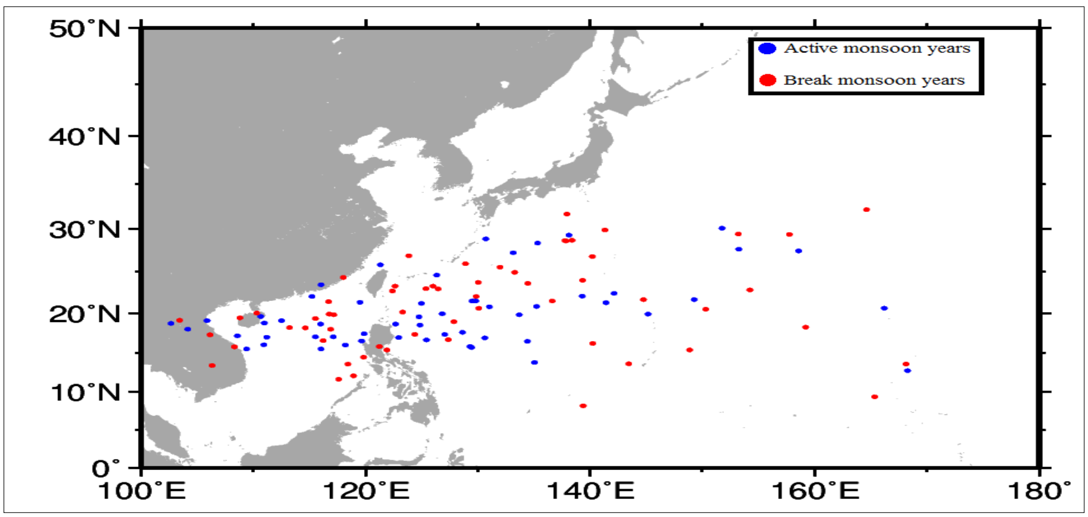

Figure 15. Mean position of combined cyclonic storm in the NWP. Blue dots indicating the active year cyclones and red dots indicating the break year cyclones.

4.2 Ocean atmosphere coupling over the indo-pacific region and the monsoon activity over India

Global warming is the scientific term used to define a steady increase in the average temperature of the Earth's atmosphere and lithosphere, and changes the Earth's climate permanently. Many researchers have studied the role of several ocean-atmosphere parameters over the Indian and Pacific sector on Indian Monsoon activity and suggested various results and conclusions. Present study is an attempt to examine the concurrent relationship of sea surface temperature (SST), southern oscillation index (SOI) and Walker circulation index (WCI) on the Indian summer monsoon activity.

4.2.1 Sea surface temperature and Indian summer monsoon

The difference in SST anomaly between the western equatorial Pacific (WEP; 120° - 130°E, 5°S - 5°N) and eastern equatorial Pacific (EEP; 80°- 90°W, 5°S - 5°N) was used as an index of the intensity of the Walker circulation (WCI), with positive(negative) WCI leading to stronger(weaker) Walker circulation. Southern Oscillation Index (SOI) has been extracted from the NOAA website. Monthly mean SST from HadISST over the five regions (REG-I to REG-V in the Fig. 5.) were used and the robustness of the result checked using ERSST dataset. Rainfall data used from different homogeneous macro regions of the Indian subcontinent was downloaded from IITM website. Macro regional and all India rainfall were used in the different sections of analysis in the study (Sontakke *et al.,* 2008).

The southern oscillation index showed high correlation with macro-regional rainfall as well as all India rainfall. REG-I, REG-II and WCI has showed reasonable correlation (Table 4) with as all India rainfall and macro-regional rainfall. Present study showed a strong correlation with rainfall over all India and north mountainous region. The southern oscillation index and REG-II showed maximum correlation with all India rainfall and its significant level was 99.9 per cent, followed by WCI, REG-I, EEP and WEP. The Northern parts (NEI, NCI, NWI and NMI) of India correlated more with the selected variables of SST than the Southern parts of India (SPI, EPI and WPI). The WEP showed least correlation with ISMR while EEP showed good and significant correlation with all the selected regions. Indian subcontinent and WEP were connected regions, while EEP is more influencing regional rainfall of India.

According to Bhalme and Jadhav (2006), the monsoon rainfall is significantly (99.9 per cent level) correlated with the Southern Oscillation indices for the seasons: May-June-July (0.59) and August-October (0.67). The fluctuations in the Southern Oscillation index for the August-October season appear strongly related to the nearly simultaneous monsoon rainfall of India. This implied that the large positive (negative) value of the Southern Oscillation index, signifying strengthening (weakening) of the Walker circulation coincided with large excess (deficient) monsoon rainfall over India.

According to Parthasarathy and Pant (1985), The SOI values of different months and standard seasons show opposite tendencies during deficient and excess years of all-India monsoon rainfall. The correlation coefficients (CC) between the all-India monsoon rainfall series and the SOI of summer monsoon (June-July-August), autumn (September-October-November) and winter (December-January-February) minus spring (March-April-May) seasons were significant at the 1 per cent level.

Chattopadhyay and Bhatla (1993) studied the relationship between the monsoon rainfall throughout all India, northwest India and peninsular India as well as the onset dates of the monsoon and two indices of southern oscillation (SOI), namely Isla de Pascua minus Darwin (I-D) and Tahiti minus Darwin (T-D) pressure anomaly for different periods. The study indicated that the monsoon rainfall shows a strong and significant direct relationship with SOI for the concurrent, succeeding autumn and succeeding winter seasons.

4.2.2 Sea surface temperature variability

The decadal analysis of sea surface temperature (1951-2010) in the Indian and Pacific oceans is presented in Fig 16.The SST in the Indo-Pacific region was found to be increased during the first (1951-1960) and second (1961-1970) decades. But a fall

Table 4. Correlation coefficients and statistical significance (super script) in the same regions (1950-2010).

	All-India	SPI	EPI	WPI	NEI	NCI	NWI	NMI
SOI	.48	.38	.12	.35	.23	.24	.39	.40
WCI	.33	.13	.11	.16	.14	.28	.27	.33
WEP	.23	.18	.13	.22	.21	.18	.14	.10
EEP	.30	.09	.09	.11	.09	.26	.27	.42
REG I	.37	.20	.17	.20	.02	.19	.36	.50
REG II	.52	.30	.17	.37	.22	.33	.43	.35

90% 95% 98% 99% 99.9%

in SST was observed during the third decade (1971-1980) compared to that of second decade. SST in the warm pool area of Indo-Pacific region was decreased during this period. The third decade onwards, an increasing trend in SST was noticed till the last decade (2001-2010). The warming observed in the central Pacific region during the second decade to fourth decade. Thereafter, the temperature in the region decreased towards the last decade which was comparable to that of first decade. Anomalous warming of western Pacific and Indian Ocean was observed decade by decade. According to Rao *et al.* (2012), Indian Ocean is consistently warming and its warm pool is expanding, particularly in the recent decades.

According to Hansen *et al.* (2005), Earth is absorbing 0.85 ± 0.15 Wm^{-2} more energy from the Sun than it is emitting to space. This imbalance is confirmed by precise measurements of increasing ocean heat content over the past 10 years. About 93 per cent of the excess heat energy stored by the earth over the last 50 years is found in the ocean (Church *et al.,* 2011).

SSTs over the Indian Ocean and west Pacific show variability on intra-seasonal timescales, with a change of up to 1–2^0C within a week or two (Roxy, 2013). Magnitude of SST warming trend is significantly stronger during the summer monsoon season than during the other seasons (Swapna *et al.,* 2014). According to Chambers (1999), SST and wind data suggest that Indian Ocean warming has occurred during several previous El-Niño events, particularly during 1982 and 1987. Based on these observation it is suggested that warming began with wind forced rossby waves in the south East Indian Ocean associated with the southern oscillation similar to the forcing of kelvin waves which precede El-Niño in the Pacific.

The difference in SST from recent decade to first decade is represented (Fig. 17) to identify the warming/cooling of the Indo-Pacific region. The Indian Ocean and west Pacific Ocean being warmed compared to that of east Pacific region. Indian Ocean is mostly covered by land in the northern side as compared with the Pacific Ocean and the differential heating over land and ocean is the reason for substantial warming of entire Indian Ocean. The increased temperature gradient between equatorial western Pacific and central Pacific region is clearly seen in the Fig. 17. Central Pacific Ocean was cooler than Eastern Pacific, which creates La-Niña type conditions (Gopika and Ramesh, 2015).

Saha (1974) pointed out that the higher SST in the Indian Ocean region would lead to higher evaporation and this will release more moisture into the atmosphere which will result in good monsoon. In the Indian Ocean, the region of SST greater than 28°C occurs south of the equator in January and expands to a large region (20°S - 20°N) during February-April (Krishnamurthy and Kirtman ,2001). According to Roxy *et al.* (2014), Indian Ocean has been warming consistently, over a century and at a faster rate than any other region of Tropical Ocean, and this may weaken the Indian monsoon circulation. During the past half-century it observed that continuously increasing warming over the Indian Ocean warm pool and Indian Ocean Sea Surface Temperature warming was the strongest and most robust warming signal around the global ocean (Lu Dong *et al.,* 2014).

The temporal series analysis of ISMR, WCI and SOI is presented in Fig 18 during 1950-2010. According to Kumar *et al*. (1999), the link with El Niño has weakened in the last decade, and in fact the ISMR anomaly was positive in the recent intense warm event of 1997. The WCI showed good correlation with ISMR rainfall during El-Niño years (red bars) and La-Niña years (blue bars). During El-Niño (La-Niña) years, the Walker circulation index showed dominant negative (positive) values and a subsequent decrease (increase) in the rainfall over Indian subcontinent. The strengthening of Walker circulation promotes cross equatorial flow which leads a good monsoon year in India. The newly created Walker circulation index is a promising tool for studying the strengthening (weakening) of the Walker circulation.

Ashok (2001) suggested that, whenever the ENSO-ISMR correlation is low (high), the IOD-ISMR correlation is high (low). The IOD plays an important role as a

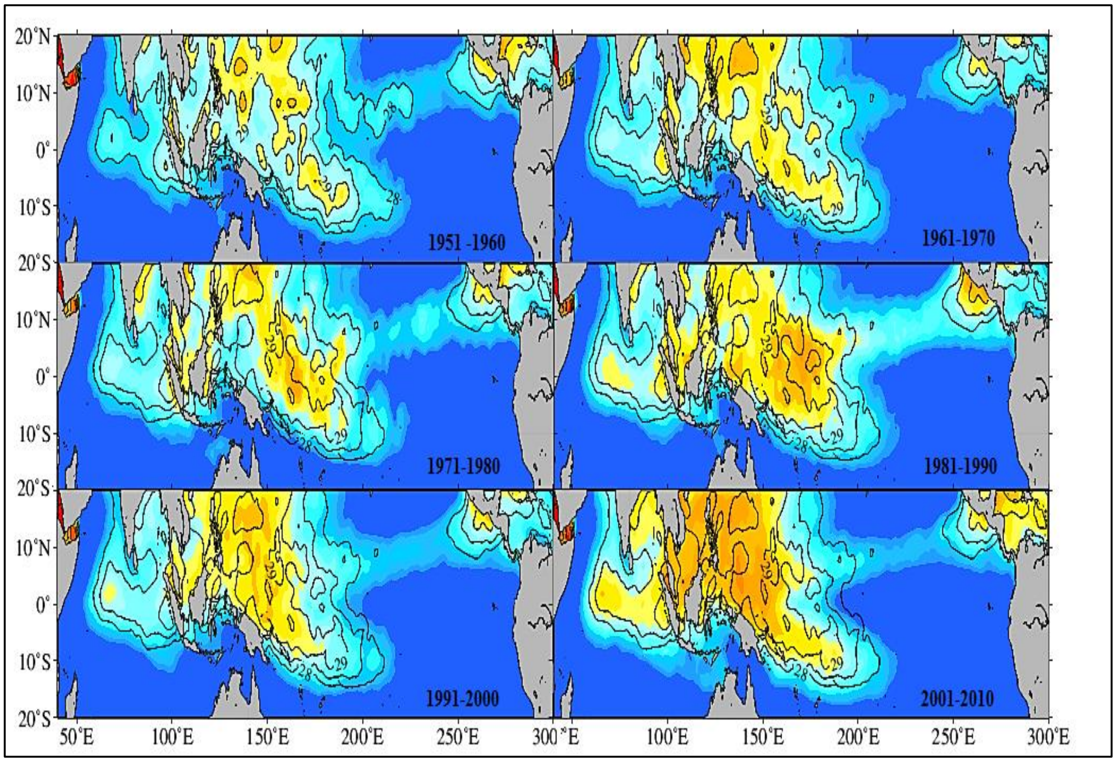

Figure 16. Decadal variation of SST in the Indo-Pacific region (1951-2010).

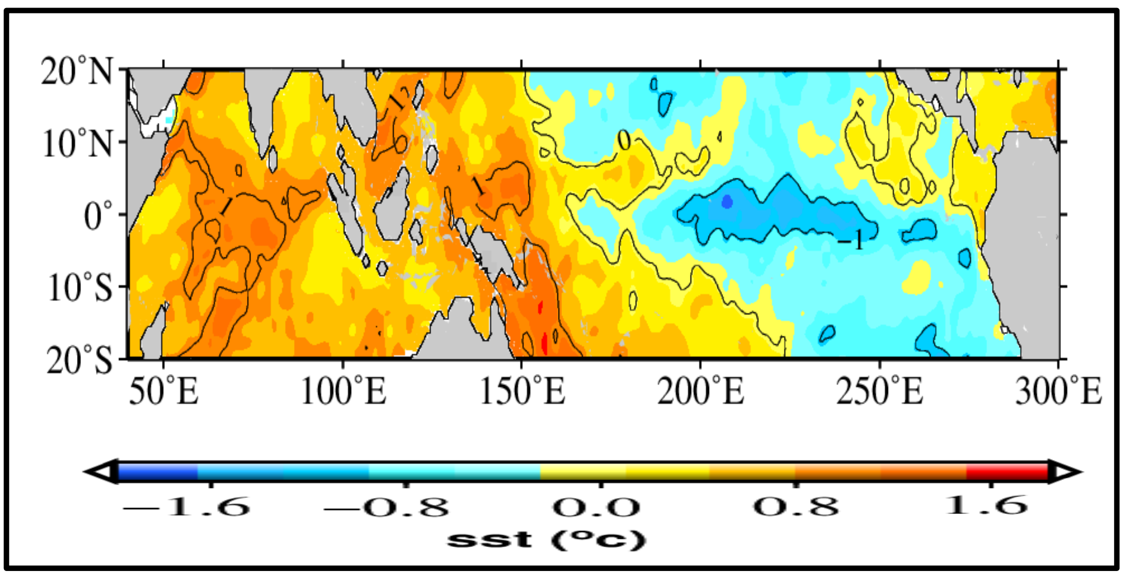

Figure 17: Warming/cooling of the Indo-Pacific region during recent decade.

modulator of the Indian monsoon rainfall and influences the correlation between the ISMR and ENSO.

Ghosh *et al.,* (2009) reported that the daily rainfall quantities and incidences of the ISMR show spatial variations due to rapid urbanization, mechanisation and deforestation. During El-Niño period the thermocline depth become deeper, while it usually set as normal. The related atmospheric modification is called the Southern Oscillation, mentioning to large scale seesaw in atmospheric pressure between the south eastern tropical Pacific and north of Australia (Bjerknes, 1966). On the other hand present study opposing the results of Sarkar *et al.* (2004), they suggested that the effect of ENSO on Indian rainfall has not decreased but on the contrary it has increased on recent times.

SSTDMI is the anomalous SST difference between REG-IV and REG-V. The time series relationship between DMI, ISMR with Niño3, Niño 3.4, Niño 4 and Niño 1+2 shown in Fig. 19, Fig. 20, Fig. 21 and Fig. 22 respectively. Niño 3.4 (-0.57904) and Niño3 (-0.52216) regions were negatively and significantly correlated with ISMR followed by Niño4 (-0.4886) and Niño1+2 (-0.3278). SSTs in the Niño 3.4 and Niño 3 regions were more correlated with ISMR during the observation period.

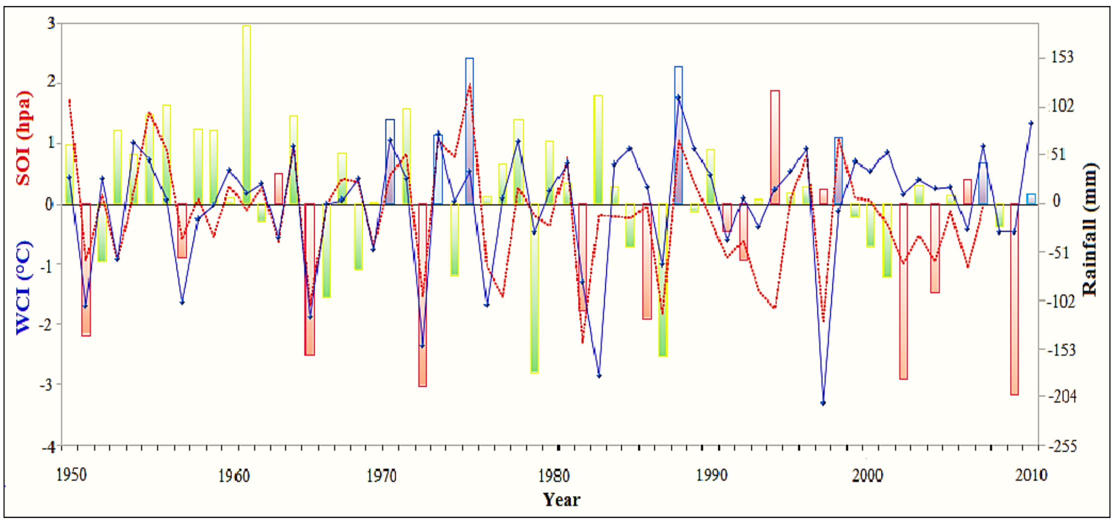

Figure 18. The time series plot of the WCI, ISMR, and SOI from 1950 to 2010. The bar diagram shows rainfall anomaly, blue line is WCI and red line is SOI. In the bar itself the colour is distinguish with green (normal year), blue (La-Niña year) and red (El-Niño year).

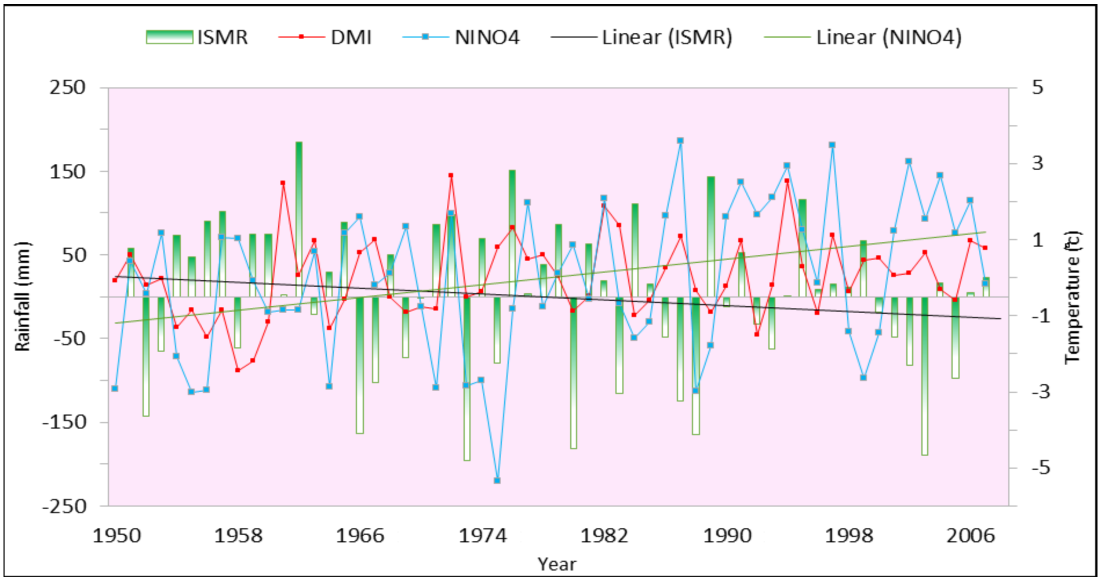

Figure 19. Time series plot of ISMR, DMI and SST over Niño 4 region.

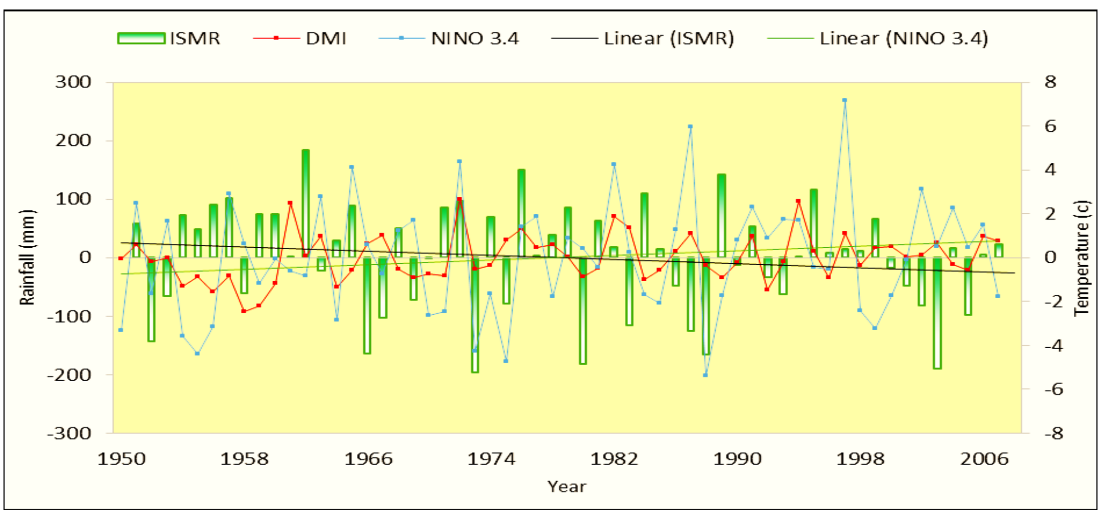

Figure 20. Time series plot of ISMR, DMI and SST over Niño 3.4 region.

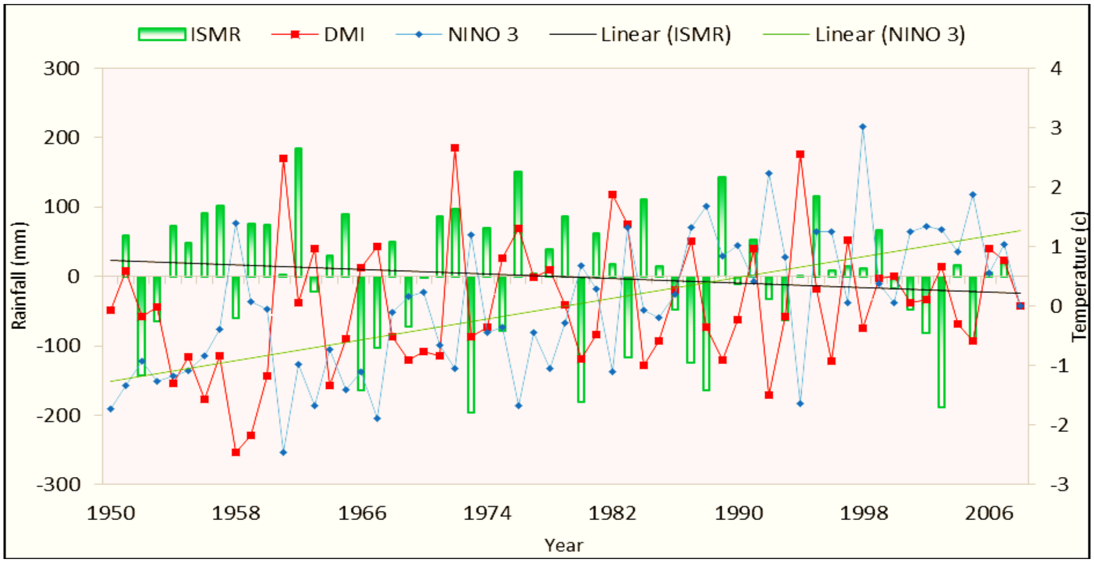

Figure 21. Time series plot of ISMR, DMI and SST over Niño 3 region.

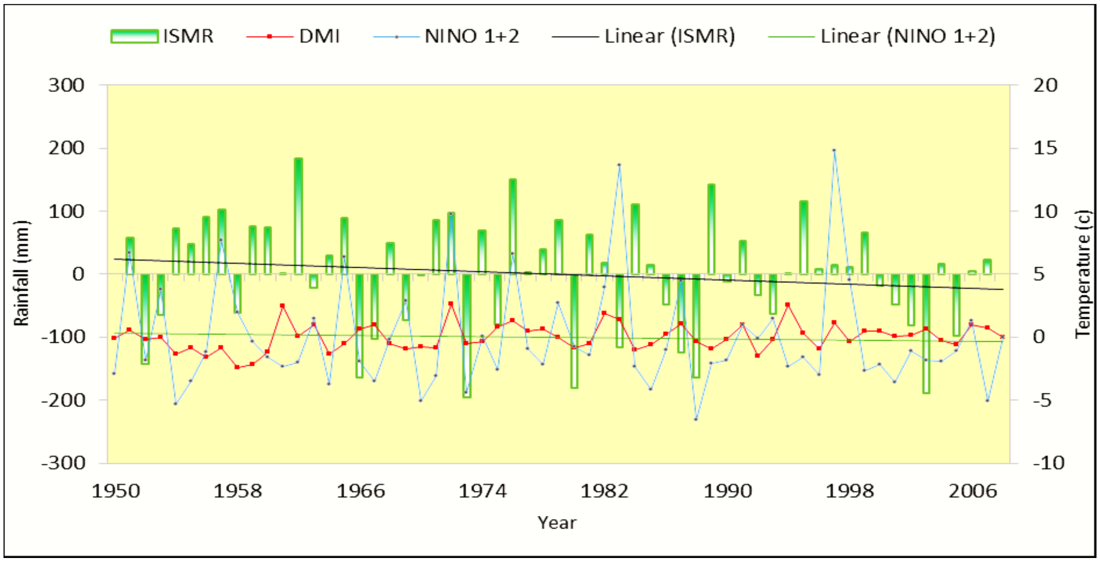

Figure 22. Time series plot of ISMR, DMI and SST over Niño 1+2 region.

SUMMARY

CHAPTER 5

SUMMARY

The role of convective activity, convective systems (NWP and NIO) and active/break days on ISMR was analysed. Present study showed that during break (active) monsoon conditions, the convection was more (less) over the Equator (Bay of Bengal). The enhanced convection over the Bay of Bengal region pulls the monsoon current (low level flow) into peninsular India and active monsoon condition prevails over the Indian subcontinent. When the convection shifts to equatorial trough region, the monsoon current avoid the Indian subcontinent leads break monsoon condition. Simultaneous correlation of various ocean atmospheric parameters over different equatorial regions were determined. It was found that the eastern equatorial trough region (90°E - 110°E; 0°- 10°S) rainfall had the maximum correlation with sea surface temperature (SST) ($r = 0.85$). This was found to be the most important meteorological phenomena and is statistically significant.

Active and break spells of Indian monsoon condition is influenced by fluctuations in tropical convergence zones. There was no significant correlation between North Indian Ocean cyclonic systems and rainfall over equatorial trough regions. In fact the driving force of the BoB cyclones are achieved from the cyclonic vorticity of NWP. The occurrence of active/break spells was due to the combined effect of slightly active equatorial and strong cyclonic activity over NWP. An increased number of convective systems in the west Pacific showed high negative correlation with rainfall over equatorial trough regions. During active monsoon years, cyclones are focused between 10° - 25° N and 110° - 140° E whereas the cyclones were widely distributed during the break monsoon years. The co-occurrence of active/break spells and convective activity have considerable influence on ISMR. During an active spell, enhanced convection was observed over NIO while during break spell it was over ET regions. Strong, widespread and short duration cyclonic activity over NWP results a break spell in ISMR.

The relative influence of the El-Niño Southern oscillation and Indian Ocean Dipole (IOD) events on the Indian summer monsoon (June-September) rainfall (ISMR) have been further studied for the period 1950-2010. Decadal analysis for the period of 1951-2010 showed an increasing trend in SST during the third decade (1971-1980) to last decade (2001-2010). The central Pacific started warming up during second decade (1961-1970) to the fourth decade (1981-1990. Thereafter, temperature of central Pacific region indicated rapid cooling in the recent decades and increased the temperature gradient between western and eastern Pacific Ocean. This cooling in the central Pacific could create La-Niña type conditions. The impact of ENSO and IOD conditions on ISMR at macro-regional scales showed that El-Niño indicators Niño1+2 (Far eastern tropical Pacific Ocean), Niño 3 (Eastern tropical Pacific Ocean), Niño 3.4 (Central tropical Pacific Ocean) and Niño 4 (Western tropical Pacific Ocean) had significant correlation with summer monsoon rainfall of India. The trend of SST at Niño 3.4 is mostly influencing the ISMR followed by Niño3. SSTs in the central Pacific (Niño 3.4; REG- II) and eastern Pacific (Niño 3; REG- III) regions were more correlated with ISMR during the observation period.

During El-Niño (La-Niña) years, the weakened (strengthened) Walker circulation influence the summer monsoon rainfall over the Indian subcontinent. During La-Niña year, the strengthened Walker circulation promotes the cross equatorial flow which leads a good monsoon year in India. The newly created Walker circulation index is a promising tool to examine the strengthening (weakening) of the Walker circulation to predict the Indian summer monsoon in future research.

REFERENCES

REFERENCES

Adler, R.F., Huffman, G. J., Chang, A., Ferraro, R., Xie, P., Janowiak, J., Rudolf, B., Schneider, U., Curtis, S., Bolvin, D., Gruber, A., Susskind, J. and Arkin, P. 2003. The Version 2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present). *J. Hydrometeor*.4:1147-1167.

Ananthakrishnan, R. and Pathan, J.M. 1981. Pentad Rainfall charts and space time variations of rainfall over India and the adjoining areas. Contributions from the Indian Institute of Tropical Meteorology, *Sci. Rep*. RR-036.

Annamalai, H. and Slingo, J. M. 2001. Active/Break cycles: Diagnosis of the intraseasonal variability of the Asian summer monsoon. *Clim. Dyn.* 18:85-102.

Ashok, K., Guan, Z. and Yamagata T. 2001. Impact of Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. *Geophys. Res. Lett*. 28: 4449 – 4502.

Bhalme, H. N. and Jadhav, S. K. 2006. The Southern Oscillation and its relation to the monsoon rainfall. *Int. J. of Climatol.* 4 (5): 509-520.

Bhaskar Rao, D.V., Naidu, C.V. and Srinivasa Rao, B. 2001. Trends and fluctuations of the cyclonic systems over North Indian Ocean. *Mausam*. 52(1): 1 – 8.

Bjerknes, J. 1966. A possible response of the atmospheric Hadley circulation to equatorial anomalies of ocean temperature. *Tellus*. 18(4):820-829.

Cadet, K.L. and Daniel, P. 1988. Long-range forecast of the break and active summer monsoons. *Tellus*. 40(A):133–50.

Cardone, V.J., Greenwood, J.G. and Cane, M. 1990. On trends in historic marine wind data. *J. Clim.* 3:113-127.

Chambers, D.P., Tapley, B. D. and Stewart, R.H. 1999. Anomalous warming in the Indian Ocean coincident with El Niño. *J. Geophys. Res*. 104(C2):3035-3047.

Chan, J.C.L. 1985. Tropical Cyclone activity in the northwest Pacific in relation to the El Ni -no/Southern Oscillation phenomenon. *Mon. Weather Rev*. 113: pp. 599–606.

Charney, J.G. 1969. The intertropical convergence zone and the Hadley circulation of the atmosphere. *Proc. WMO/IUCG Symp. Nubmer. Weather Predict*. Japan Meteorological Agency. III: 73–79.

Charney, J. G. and Shukla, J. 1981. Predictability of monsoons. Monsoon Dynamics, *J. Lighthill*. 99-109.

Chattopadhyay, J. and Bhatla, R. 1993. Influence of southern oscillation index on the variability and predictability of Indian monsoon. A reappraisal. *Pure and Appl. Geol.* 144 (1): 177-188.

Church, J. A., White, N.J., Konikow, L., Domingues, C.M., Cogley, J.G., Rignot, E. and Gregory, J.M. 2011. Revisiting the Earth's sea-level and energy budgets from 1961 to 2008. *Geophys. Res. Lett.*, 38(18):L18601.

Clark, C. O., Cole, J. E. and Webster, P. J. 2000. Indian Ocean SST and Indian summer rainfall: Predictive relationships and their decadal variability. *J. Clim*., 13:2503-2519.

De, U. S., Prasad, O. and Vaidya, D. V. 1995. The influence of Southern hemispheric equatorial trough on rainfall during Southwest monsoon. *Theor. Appl. Climatol*. 52:177-181.

Flatau, M. K., Flatau, P. J., Schmidt, J. and Kiladis, G. N. 2003. Delayed onset of the 2002 Indian monsoon, *Geophys. Res. Lett*. 30:1768.

Gadgil, S. 2003. The Indian monsoon and its variability. *Annu. Rev. of Earth and Planetary Sci.* 31(1):429–467.

Gadgil, S., and Jospeh, P.V., 2003. On the breaks of the Indian Monsoon, *Proc. of Indian Acad. of Sci. (Earth and Planetary Sci.)*. 112: 529-558.

Gadgil, S., Vinayachandran, P.N. and Francis, P.A. 2003. Drought of Indian summer monsoon: Role of cloud over Indian Ocean. *Curr. Sci.* 85:1713-1719.

Ghosh, S., Luniya, V. and Gupta, A. 2009. Trend analysis of Indian summer monsoon rainfall at different spatial scale. *Atmos. Sci. Lett*. 10(4):285–290.

Godfrey, J.S., Alexiou, A., lIahude, A.G., Legler, D.M., Luther, M.E., McCreary Jr, J.P., Meyers, G.A., Mizuno, K., Rao, R.R., Shetye, S.R., Toole, J.H. and Wacongne, S. 1995 . The role of the Indian Ocean in the global climate system: Recommendations regarding the global ocean observing system. *Report of the Ocean Observing System Development Panel*, Texas A and M University, College Stn.TX, USA. 89p.

Gopika, S. and Ramesh Kumar, M.R. 2015. Ocean atmosphere coupling over the indo-pacific region and the monsoon activity over India. *Proc. of OSICON-2015 conf.*120p.

Goswami, B. N. and Mohan, A.R.S. 2001. Intra-seasonal oscillations and inter-annual variability of the Indian summer monsoon, *J. Clim.* 14: 1180-1198.

Goswami, B. N. and Xavier, P. R. 2005. ENSO control on the south Asian monsoon through the length of the rainy season, *Geophys. Res. Lett*. 32: L18717.

Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S. and Xavier, P. K. 2006.Increasing trend of extreme rain events over India in a warming environment. *Sci*. 314:1442–1445.

Graham, N. E. and Barnett, T. P. 1987. Sea surface temperature, surface wind divergence and convection over tropical oceans. *Sci*. 238:657-659.

Halley, E. 1686. Historical account of the trade winds and monsoons. *Philosophical Trans. of the R. Soc. Lond.* 16: 153–168.

Han, W. and Webster, P. J. 2002. Forcing mechanisms of sea level inter-annual variability in the Bay of Bengal. *J. of Phys. Oceanogr*. 32:216–239.

Hansen, J., Nazarenko, L., Ruedy, R., Sato, M. and Willis, J. 2005. Earth's energy imbalance: Confirmation and implications, *Sci*. 308(5727):1431–1435.

IMD [Indian Meteorological Department]. 2015. *IMD monsoon home page* [on-line].Available:http://www.imd.gov.in/section/nhac/dynamic/Monsoon_frame.htm [05 Jun. 2015].

Ihara, C., Kushnir, Y. and Mark, A. C. 2008, Warming Trend of the Indian Ocean SST and Indian Ocean Dipole from 1880 to 2004, *J. Clim*. 2035:2046.

Joseph, P. V. and Sijikumar, S. 2004. Intra-seasonal variability of the low-level jet stream of the Asian summer monsoon. *J. of Clim*. 17:1449–1458.

Joseph, P.V. and Pillai, P.V. 1984. Air sea interaction over the north Indian Ocean –part I. Inter-annual variation of sea surface temperature and Indian summer monsoon rainfall. *Mausam*. 35:323-330p.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell,M., Saha, S., White, G., Woollen, J., Zhu, Y., Leetmaa, A., Reynolds, R., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Jenne, R. and Joseph, D. 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bull. Amer. Meteor. Soc. 77: 437–471.

Krishnamurthy, V. and Kirtman, B. P. 2001. Variability of the Indian Ocean: Relation to monsoon and ENSO. *COLA Tech. Rep.* 107:pp.40.

Krishnamurthy, V. and Kinter, J. L. 2002. The Indian Monsoon and its Relation to Global Climate Variability. In: Xavier, R. and Francisco, A. C. (eds), *Global climate* . Springer- Verlag Berlin Heidelberg New York. pp. 186-222.

Krishnamurthy, V. and Shukla, J. 2000: Intraseasonal and Interannual Variability of Rainfall over India. *J. Climate*. 13:4366–4377.

Krishnan, R., Zhang, C. and Sugi, M. 2000. Dynamics of breaks in the Indian summer monsoon. *J. Atmos. Sci*. 57:1354–72.

Kumar, K.K., Rajagopalan, B., Cane, M.A. 1999. On the weakening relationship between the Indian monsoon and ENSO. *Sci.* 284:2156–59.

Liebmann, B. and Smith, C.A. 1996. Description of a Complete (Interpolated) Outgoing Longwave Radiation Dataset. Bull. of the Am. Meteorological Soc. 77:1275-1277.

Lu Dong and Tianjun Zhou. 2014. The Indian Ocean Sea Surface Temperature Warming Simulated by CMIP5 Models during the Twentieth Sentury: Competing Forcing Roles of GHGs and Antropogenic Aerosols, *Am. Meterological Soc.* 27:3384-3362.

McPheden, J. M. 2004. Evolution of the 2002/2003 El Niño. *Am. Meterological Soc*. 677-695.

Meehl, G. A. 1987. The annual cycle and its relationship to inter-annual variability in the tropical Pacific and Indian Ocean regions. *Mon. Wea. Rev.* 115:27-50.

Mishra, D.K. 1981. Satellite derived sea surface temperature distribution over the north Indian Ocean during southwest monsoon season, *Mausam*, 32:59-66p.

Pai, D.S. and Rajeevan, M. 2007. Indian summer monsoon onset: Variability and Prediction. *J. of Earth Syst. Sci.* 118 (2): 123-135.

Parthasarathy, B. and Pant, G. B. 1985.Seasonal relationships between Indian summer monsoon rainfall and the southern oscillation. *J. Climatol.* 5: 369–378.

Pearce, R. P. and Mohanty, U. C. 1984. Onset of the Asian summer monsoon1979- 1982, *J. of Atmos. Sci*. 41:1620-1639.

Prasad, V. S. and Hayashi, T. 2005. Onset and withdrawal of Indian summer monsoon, *Geophys. Res. Lett.* 32:L20715.

Raghavan, K. 1973. Break monsoon over India. *Mon. Weather Rev.* 101:33–43.

Rajeevan, M., Gadgil, S. and Bhatem, J. 2010. Active and break spells of the Indian summer monsoon. *J. Earth Syst. Sci.* 119(3): 229-247.

Ramage, C.S. 1971. Monsoon Meteorology. *Int. Geophys. Ser*. 296p.

Ramesh Kumar, M. R., Babu, A. K. and Chris Reason. 2009a. On the role of convective systems over the northwest Pacific and monsoon activity over the Indian subcontinent. *Meteorol. Appl*. Vol.16:353–360.

Ramesh Kumar, M. R. and Dessai U. R. P 2004. A new criterion for identifying breaks in monsoon conditions over the Indian subcontinent, *Geophys. Res. Lett*. 31:L18201.

Ramesh Kumar, M.R., Krishnan, R., Syam Sankar, Unnikrishnan, A.S. and Pai, D.S. 2009b. Increasing trend of Break-Monsoon Conditions over India-Role of Ocean-Atmosphere processes in the Indian Ocean, *IEEE Geosience And Remote Sensing Lett.* 6(2):332-336.

Ramesh Kumar, M.R. and Sankar, V. 2010. Impact of global warming on cyclonic storms over north Indian Ocean, *Indian J. of Geo-Mar. Sci.* 394(4):516-520.

Ramesh Kumar, M. R. Shenoi, S. S. C. and Shulz, J. 2005. Impact of convection over the equatorial trough on summer monsoon activity over India. *Int. J. of Remote Sensing.* 26(21): 4747–4762.

Rao Krishna, P. R, and Jagannathan, P. 1953. A study of Northeast monsoon rainfall Tamilnadu. *Indian J. of Meteorol. and Geophy*. 4: 22-43.

Rao, K, G., Desbois, M., Rocca, R. O. and Nakmura, K. 2004. Upper tropospheric drying and the transition to break in the Indian summer monsoon during 1999: *Geophys. Res. Lett.* 31(3): GLO18269.

Rao, S. A., Dhakate, A. R., Saha, S. K., Mahapatra, S., Chaudhari, H. S., Pokhrel, S. and Sahu, S. K. 2012. Why is Indian Ocean warming consistently? , *Climatic Change*. 110:709–719.

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C. and Kaplan, A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century *J. Geophys. Res*. 108: D14.

Revadekar, J. V. and Preethi, B. 2012. Statistical analysis of the relationship between summer monsoon precipitation extremes and food grain yield over India. *Int. J. of Climatol*. 32(3):419–429.

Roxy, M. 2013. Sensitivity of precipitation to sea surface temperature over the tropical summer monsoon region—and its quantification. *Clim. Dyn*. 43(5-6): 1159-1169.

Roxy, M., Ritika, K., Terray, P. and Masson, S. 2014. The curious case of Indian Ocean warming. *J. of Clim*. 27(22): pp.8501-8509.

Roxy, M., Tanimoto, Y., Preethi, B., Terray, P. and Krishnan, R. 2013. Intra seasonal SST–precipitation relationship and its spatial variability over the tropical summer monsoon region. *Clim. Dyn*. 41:45–61.

Saha, K.R., 1974. Some aspects of the Arabian Sea summer monsoon. *Tellus*, 26(4): 464-476.

Saji, N.H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T. 1999. A dipole mode in Tropical Indian Ocean. *Nat*. 401:360-363.

Sarkar, S., Singh, R. P. and Kafatos, M. 2004. Further evidences for the weakening relationship of Indian rainfall and ENSO over India, *Geophys. Res. Lett*. 31: L13209.

Sengupta, D. and Ravichandran, M. 2001. Oscillation of the Bay of Bengal, SST during the 1998 summer monsoon, *Geophys. Res. Lett*., 28(10): 2033-2036.

Shukla, J. 1987. Inter-annual variability of monsoons. *Monsoons.* 399-463.

Shukla, J. and Misra, B.M. 1977. Relationships between Sea Surface Temperature and Wind Speed over the central Arabian Sea, and Monsoon Rainfall over India. *Mon. Weather Rev.* 105:998-1002.

Sikka, D. R. and S. Gadgil. 1980. on the maximum cloud zone and the ITCZ over Indian longitudes during the southwest monsoon. *Mon. Weather Rev.* 108:1840-1853.

Simon, B., Rahman, S. H., Joshi, P. C. and Desai, P. S. 2008. Shifting of the convective heat source over the Indian Ocean region in relation to performance of monsoon: A satellite perspective. *Int. J. of Remote Sensing* 29(2):387–397.

Sontakke, N.A. Singh, N. and Singh, H.N. 2008. Instrumental period rainfall series of the Indian region (1813-2005): revised reconstruction, update and analysis. *The Holocene*. 18(7):1055-1066.

Swapna, P., Jianping Gan**,** Alexis Lau and Jimmy Fung. 2009. On the warm/cold regime shift in the South China Sea: Observation and modelling study. *Deep Sea Res.I*. 56:1039–1056.

Tschuck, P., Chauvin, F., Dong, B. and Arpe, K. 2004. Impact of Sea-Surface temperature anomalies in the equatorial Indian Ocean and Western Pacific on the Asian Summer Monsoon in the General Circulation Models," *Int. J.of Climatol.* 24: pp. 181-191.

Vijay, G. 2014. Outgoing Longwave Radiation (OLR) a proxy of convection. *Int. J. of Eng. Res. and Manag. Technol.* 1 (1): 2348:4039.

Vinay Kumar. and Krishnan, R. 2005. On the association between the Indian summer monsoon and the tropical cyclone activity over the Northwest Pacific. *Curr. Sci*. 88 (4):602-612.

Wang, Bin., Webster, P.J., and Teng, H. 2005. Antecedents and self-induction of active-break south Asian monsoon unraveled by satellites.*Geophys. Res. Lett*., 32: L04704.

Weare, C. B. 1979. A Statistical Study of the Relationships between Ocean Surface Temperatures and the Indian Monsoon. *J. Atmos. Sci.*36:2279–2291.

Webster, P.J., Magana, V. O., Palmer, T.N., Shukla, J., Tomas, R. A., Yanai, M. and Yasunari, T. 1998. Monsoons: Processes, predictability, and the prospects for prediction. *J. Geophys. Res.*103 (14):451-14,510.

Yanh Zhou, Anning Huang, Yong Zhao, Qing Yang, Jing Jiang and Mengke La. 2014. Influence of the sea surface temperature anomaly over the Indian Ocean in march on the summer rainfall in Xinjiang, *Theor. Appl. Climatol.* 119 (3-4):781-789.

Yin, Xungang., Gruber, A., and Arkin, P., 2004. Comparison of the GPCP andCMAP Merged gauge satellite monthly precipitation products for the period1979-2001. *J. of Hydrometeorology*. 5:1207-1222.

APPENDIX -I

The chart colour codes intensity in Unisys hurricane (category based on Saffir-Simpson scale):

Type	**Category**	**Pressure (mb)**	**Winds (knots)**	**Winds (mph)**	**Line Color**
Depression	TD	-----	< 34	< 39	Green
Tropical Storm	TS	-----	34-63	39-73	Yellow
Hurricane	1	> 980	64-82	74-95	Red
Hurricane	2	965-980	83-95	96-110	Light Red
Hurricane	3	945-965	96-113	111-130	Magenta
Hurricane	4	920-945	114-135	131-155	Light Magenta
Hurricane	5	< 920	> 135	> 155	White

APPENDIX -II

- Monsoon break spells

1979	2–6J, 14–29A
1980	17–20J, 13–15A
1981	24–27A
1982	1–8J
1983	23–25A
1984	27–29J
1985	23–25A
1986	22–31A
1987	23–25J, 30J–4A, 8–13A, 16–18A
1988	14–17A
1989	18–20J, 30J–3A
1990	–
1991	–
1992	4–11J
1993	20–23J, 7–13A, 22–28A
1994	–
1995	3–7J, 11–16A
1996	10–12A

1997	11–15J, 9–14A
1998	20–26J, 16–21A
1999	1–5J, 12–16A, 22–25A
2000	1–9A
2001	31J–2A, 26–30A
2002	4–17J, 21–31J
2003	–
2004	10–13J, 19–21J, 26–31A
2005	7–14A, 24–31A
2006	–
2007	18–22J, 15–17A
2008	16-21A, 21-24A, 28-30A
2009	29J-10A, 17-19A

APPENDIX -III

- Monsoon active spells

1979	3–5A, 7–12A
1980	1–3J 1981 7–10J
1982	12–14A, 17–23A
1983	18–21J, 18–20A
1984	3–6A, 9–11A, 15–19A
1985	15–17J, 30J–3A, 6–9A
1986	21–24J, 13–15A
1987	24–29A
1988	26–28J
1989	–
1990	21–24A, 29–31A
1991	29–31J
1992	26–29J, 16–18A
1993	7–9J, 15–18J
1994	2–4J, 9–17J, 18–20A, 25–27A
1995	18–25J
1996	24–28J, 19–22A

1997	30J–1A, 20–26A
1998	3–6J
1999	–
2000	12–15J, 17–20J
2001	9–12J
2002	–
2003	26–28J
2004	30J–1A
2005	1–4J, 27J–1A
2006	3–6J, 28J–2A, 5–7A, 13–22A
2007	1–4J, 6–9J, 6–9A
2008	10-12 A
2009	13-16J, 21-23J

APPENDIX -IV

Values of Correlation Coefficient for different level of significance.

df	.1	.05	.02	.01	.001
1	.98769	.99692	.999507	.999877	.9999988
2	.9000	.9500	.9800	.9900	.99900
3	.8054	.8783	.9343	.9587	.99116
4	.7293	.8114	.8822	.9172	.97406
5	.6694	.7545	.8329	.8745	.9507
6	.6215	.7067	.7887	.8343	.9249
7	.5822	.6664	.7498	.7977	.8982
8	.5494	.6319	.7155	.7646	.8721
9	.5214	.6021	.6851	.7348	.8471
10	.4973	.5760	.6581	.7079	.8233
11	.4762	.5529	.6339	.6835	.8010
12	.4575	.5324	.6120	.6614	.7800
13	.4409	.5139	.5923	.6411	.7603
14	.4259	.4973	.5742	.6226	.7420
15	.4124	.4821	.5577	.6055	.7246
16	.4000	.4683	.5425	.5897	.7084
17	.3887	.4555	.5285	.5751	.6932
18	.3783	.4438	.5155	.5614	.6787
19	.3687	.4329	.5034	.5487	.6652
20	.3598	.4227	.4921	.5368	.6524
25	.3233	.3809	.4451	.4869	.5974
30	.2960	.3494	.4093	.4487	.5541
35	.2746	.3246	.3810	.4182	.5189
40	.2573	.3044	.3578	.3932	.4896
45	.2428	.2875	.3384	.3721	.4648
50	.2306	.2732	.3218	.3541	.4433
60	.2108	.2500	.2948	.3248	.4078
70	.1954	.2319	.2737	.3017	.3799
80	.1829	.2172	.2565	.2830	.3568
90	.1726	.2050	.2422	.2673	.3375
100	.1638	.1946	.2301	.2540	.3211

IMPACT OF CONVECTION OVER THE EQUATORIAL TROUGH ON INDIAN SUMMER MONSOON ACTIVITY

by

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(2010-20-118)

ABSTRACT OF THE THESIS

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2015

ABSTRACT

The existence or nonexistence of break and active cycle of rainfall over the Indian subcontinent during the mid-monsoon months of July and August decides the success and failure of Indian monsoon rainfall. Effect of active or break cycle, convective systems and convection over the equatorial trough (ET) on Indian summer monsoon rainfall (ISMR) were studied. An increased number of convective systems in the west Pacific showed high negative correlation with rainfall over equatorial trough regions. During active monsoon years, cyclones are focused between 10° - 25° N and 110° - 140° E whereas the cyclones were widely distributed during the break monsoon years. The co-occurrence of active or break spells and convective activity have considerable influence on ISMR. During an active spell, enhanced convection was observed over North Indian Ocean (NIO) while during break spell it was over ET regions. Strong, widespread and short duration cyclonic activity over North West Pacific (NWP) resulted in a break spell in ISMR.

The relative influence of El-Niño Southern oscillation and Indian Ocean Dipole (IOD) events on ISMR have been further studied for the period 1950-2010. In order to look into the role of El-Niño on the monsoon, the SST data over five regions (REG-I to REG-IV) were studied. SSTs in the central Pacific (Niño 3.4; REG- II) and eastern Pacific (Niño 3; REG- III) regions were more correlated with ISMR during the observation period. Decadal analysis showed that the temperature of central Pacific region indicated rapid cooling in the recent decades and increased the temperature gradient between western and eastern Pacific Ocean. This cooling in the central Pacific could create La-Niña type conditions. During El-Niño (La-Niña) years, the weakened (strengthened) Walker circulation influence the summer monsoon rainfall over the Indian subcontinent. The newly created Walker circulation index is a promising tool to examine the strengthening (weakening) of the Walker circulation to predict the Indian summer monsoon in future research.