Response of Eastern Arabian Sea to extreme climatic events with special reference to selected pelagic fishes

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In partial fulfilment of the Requirements for the Award of the Degree of

Doctor of Philosophy

In

Physical Oceanography

Under the Faculty of Marine Sciences

by

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Declaration

I hereby declare that the thesis entitled "**Response of Eastern Arabian Sea to extreme climatic events with special reference to selected pelagic fishes**" is an authentic record of research work carried out by me, under the supervision and guidance of Dr. R. Sajeev, Associate Professor & Head, Department of Physical Oceanography, School of Marine Sciences, Cochin University of Science and Technology, Kochi-16., in partial fulfilment of the requirement for the Ph. D degree of the Cochin University of Science and Technology in the faculty of Marine Sciences and that no part of this has been presented before for the award of any other degree in any university.

Kochi – 16
26th July 2011

Thara K J

Certificate

*I hereby certify that the thesis entitled "**Response of Eastern Arabian Sea to extreme climatic events with special reference to selected pelagic fishes**" is an authentic record of the research work carried out by **Mrs. Thara K. J.**, Full-time Research Scholar (Reg. No. 2959) under my supervision and guidance at the Department of Physical Oceanography, School of Marine Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph. D degree of Cochin University of Science and Technology under the Faculty of Marine Sciences and no part thereof has previously presented for the award of any degree, diploma or associateship in any university.*

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Thara K J

Dedicated to……..

my family

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ACF	Auto Correlation Function
AGCM	Atmospheric General Circulation Model
ARIMA	Auto-Regressive Integrated Moving Average
ASHSW	Arabian Sea High-Salinity Watermass
AVHRR	Advanced Very High Resolution Radiometer
CCF	Cross Correlation Function
CMAP	Climate prediction center Merged Analysis of Precipitation
CMFRI	Central Marine Fisheries Research Institute
CTD	Conductivity–Temperature–Depth
DMI	Dipole Mode Index
E	East
EACC	East African Coastal Current
EAS	Eastern Arabian Sea
ECC	Equatorial Counter Current
ECMWF	European Center for Medium Range Weather Forecast
EEZ	Exclusive Economic Zone
EICC	East India Coastal Current
ENSO	El Niño-Southern Oscillation
et al.	et alii (Latin word meaning ‘and others’)
FAO	Food and Agriculture Organization
Fig.	Figure
GSFC	Goddard Space Flight Center
IITM	Indian Institute of Tropical Meteorology
ILD	Isothermal Layer Depth
IOD	Indian Ocean Dipole
IPCC	International Panel for Climate Change

ISM	Indian Summer Monsoon
ISMR	Indian Summer Monsoon Rainfall
lat	Latitude
LH	Laccadive High
LHF	Latent Heat Flux
LL	Laccadive Low
long	Longitude
LTA	Local Temperature Anomaly
LWR	Long Wave Radiation
MLD	Mixed Layer Depth
N	North
NASA	National Aeronautics and Space Administration
NCEP	National Centers for Environmental Prediction
NEC	North Equatorial Current
NHF	Net Heat Flux
NIODC	National Institute of Oceanography Data Centre
NODC	National Oceanographic Data Center
OAFlux	Objectively Analyzed air-sea Fluxes
OGCM	Ocean General Circulation Model
ORA-S3	Ocean Re-Analysis System 3
PACF	Partial Auto Correlation Function
PDO	Pacific Decadal Oscillation
PFP	Pelagic Fisheries Project
PGW	Persian Gulf Watermass
PO-DAAC	Physical Oceanography-Distributed Active Archive Center
psu	Practical salinity unit
RSMAS	Rosential School of Marine and Atmospheric Science
RSW	Red Sea Watermass

S	South
SC	Somali Current
SEAS	South Eastern Arabian Sea
SeaWiFS	Sea viewing Wide Field of view Sensor
SHF	Sensible Heat Flux
SMC	Summer Monsoon Current
SMR	Summer Monsoon Rainfall
SODA	Simple Ocean Data Assimilation
SOI	Southern Oscillation Index
SPSS	Statistical Package for the Social Sciences
SSH	Sea Surface Height
SSHA	Sea Surface Height Anomaly
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SSTA	Sea Surface Temperature Anomaly
SWR	Short Wave Radiation
TAO	Tropical Atmosphere Ocean
TOGA	Tropical Ocean Global Atmosphere
UI	Upwelling Index
UNDP	United Nations Development Programme
viz.	videlicet (Latin word meaning ‘namely’)
WICC	West India Coastal Current

PREFACE

Fisheries play an important role in the world economy and so, exploitation of fishery resources has become a major conservation issue on global scale. Nowadays, the climatic change and its affects on environment as well as fishery is a major issue. Still there are not much studies has been explored in this context. The thesis attempts to study the changes in oceanographic parameters associated with extreme climatic events and its impacts on major pelagic fishery.

The thesis has been organized into six chapters, in which Chapter 1 contains the general introduction which describes the major climatic events, responses of oceans to these climatic events, the influence of oceanographic as well as meteorological parameters on fishes. The characteristics of major pelagic fishes of southwest coast of India (Oil sardine and Indian mackerel) have been described here. A description on study area and period of study is also described in this chapter. The scope and objectives of the study are also emphasized here. Chapter 2 presents review of literature in the relevant fields of the present study.

Chapter 3 includes the impact of extreme climatic events on the oceanographic variability of Eastern Arabian Sea. The extreme climatic event, the Indian Ocean Dipole associated with El Niño Southern Oscillation is taken into consideration. Chapter 4 explains the variability in oil sardine and mackerel landings of southwest coast of India during the study period. The trend analysis of the landings has been done and also a prediction model is applied for the landings. The influence of environmental parameters on oil sardine as well as mackerel fishery has been explained in Chapter 5. With regression analysis, the significant relation between environmental parameters and fish landings are also been recognized. The prediction of landings is done with these environmental parameters. Summary and conclusion with limitations and scope for future work are presented in Chapter 6. The literature used for this study is incorporated in the last session under references.

Chapter 1

INTRODUCTION

Global climate is largely governed by the oceans, which is the principal component of hydrosphere. Approximately 71% of the earth's surface is covered by sea, which still remains unexplored. The variability in sea water temperature, salinity, dissolved oxygen and chlorophyll *a* concentration influences the marine flora and fauna. Hence, the influence of climate variation on marine fisheries is very strong and complex (Ilmo and Taivo, 1961). The changes in the aquatic environment influence the recruitment, survival and growth of fish. Information on the physical, chemical and biological parameters is important in locating and exploiting marine fishery resources. Direct evidence of biological impacts due to climate change is, however, difficult to detect due to the interference of natural variations itself on spatial and temporal scales. The climatic change has become a major issue and is running on an unexpected scale. Earlier studies have shown that the oceans play a major role in the climate variability (Alexander, 1992; Sutton and Hodson, 2003; Rizzoli and Stone, 2009). The oceanic circulation including upwelling/downwelling and eddies/meanders can change rapidly resulting in climatic variations. Other factors like solar energy and green house gases also alter the thermohaline distribution in the oceanic systems.

The tropical oceans play very important roles in the natural variability of the world climate. Tropical Pacific Ocean is found to change the global weather and climate through a major phenomenon of El Niño-Southern Oscillation (ENSO; McPhaden *et al*., 1998), causing floods, droughts and a reduction in the fishery. Hence, ENSO is of worldwide concern because it affects many countries (Annamalai and Murtugudde, 2004a; Santos, 2006). Nowadays, the climatic variability in the tropical Indian Ocean has also been a subject of hot debate because Indian Ocean is found to sustain a coupled mode, known as Indian Ocean Dipole (IOD; Saji *et al.*, 1999), which affects the climate of all the countries bordering it. The interplay between ENSO and IOD drives climatic extremes in and around the Indian Ocean. The oceanographic as well as atmospheric changes brought during such extreme events are found to affect the marine life (Glynn, 1984; Beamish, 1993; Francis *et al.*, 1998; Penuelas and Filella, 2001; Learmonth *et al.*, 2006). In this work, the environmental changes during the extreme climatic events (ENSO and IOD) affecting the pelagic fishery of Eastern Arabian Sea (EAS) are presented.

1.1 Major Climatic Events

1.1.1 El Niño-Southern Oscillation (ENSO)

ENSO is a coupled ocean-atmosphere phenomenon which occurs in the tropical Pacific Ocean. ENSO has two phases, viz the warm event (El Niño) and the cold event (La Niña). These effects were first studied in 1923 by Sir Gilbert Thomas Walker from whom the Walker circulation, an important aspect of the Pacific ENSO phenomenon, was named (Fig. 1.1). Warm events during ENSO and its climate induced shifts in the Pacific have revealed considerable disruption of many commercial fisheries (Mysak, 1986; Mantua *et al.*, 1997). These events showing interannual variability have profound consequences to the climate and the ocean ecosystem. The atmospheric signature of ENSO (Southern Oscillation) is reflected by the seasonal fluctuations in the air pressure gradient between Tahiti (South America) and Darwin (Australia).

In normal years, the atmospheric pressure over the eastern Pacific is greater than that over the western Pacific. Normally, the winds over South America blow from east to west, while upwelling of cold, nutrient-rich water occurs along the western coast. During El Niño years, the winds are weak and the warm water in the western Pacific moves eastward. As this warm water piles up in the east, the upwelling of cold, nutrient-rich water along the eastern Pacific is inhibited. La Niña years are similar to the normal years, but the pattern is intense so that Sea Surface Temperature (SST) is colder than usual in the central and eastern Pacific. This is quite normal, but the swift currents increase the convection over Indonesia. Figure 1.2 shows the tropical Pacific Ocean during ENSO and normal situations. The variability of thermocline during these events is also shown.

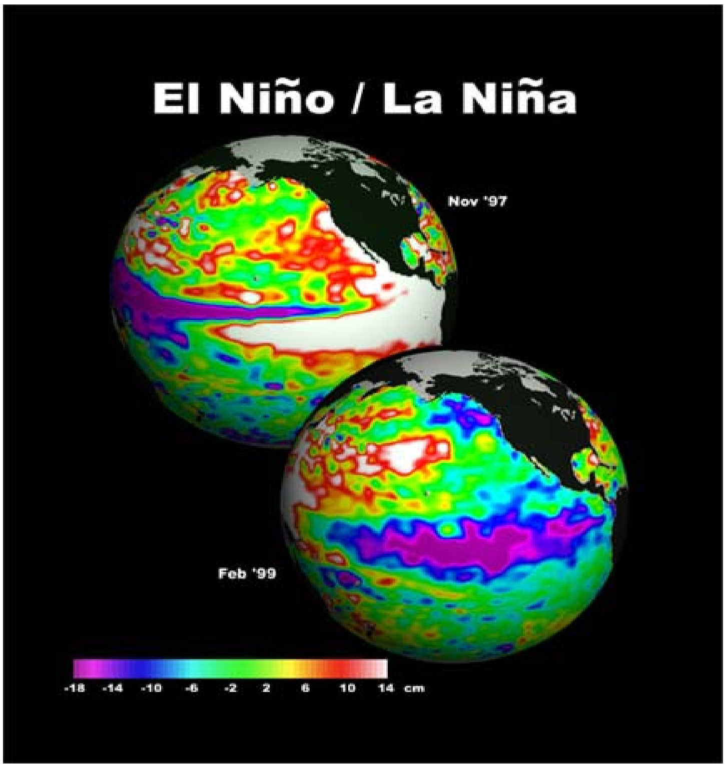
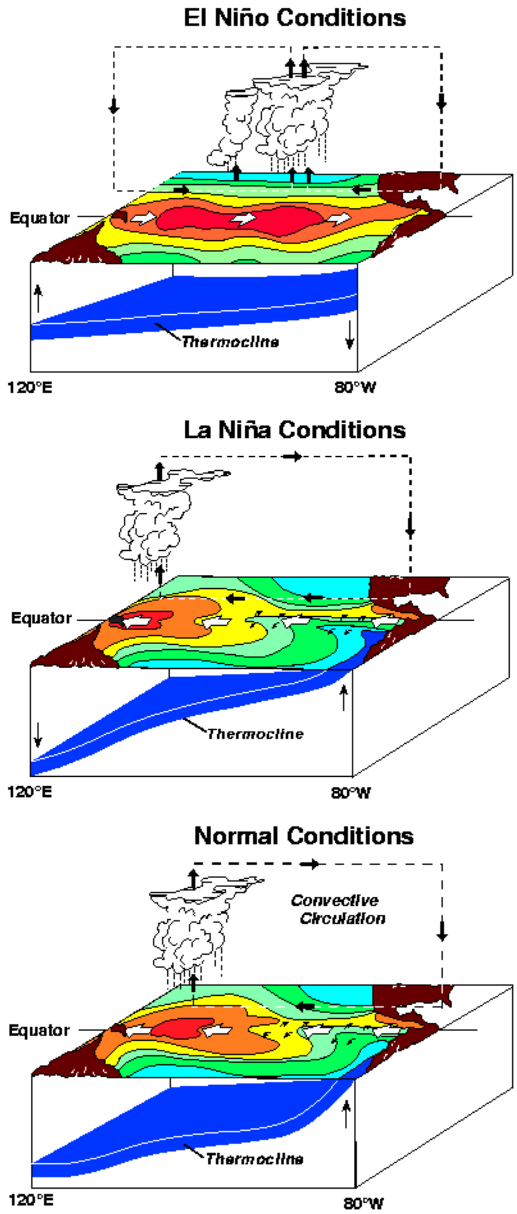


Fig. 1.1 El Niño-Southern Oscillation of Pacific Ocean
(Source: http://www.ncdc.noaa.gov)



Warm water pool approaches South American coast. Absence of cold upwelling increases warming.

Warm water is farther west than usual.

Equatorial winds gather warm water pool toward west. Cold water upwells along South American coast.

Fig. 1.2 El Niño, La Niña and Normal conditions of the tropical Pacific Ocean (Source: NOAA/PMEL/TAO)

ENSO is also associated with wide spread floods, droughts, and other disturbances and, is the most prominent source of interannual variability in weather and climate around the world. ENSO signatures are found in the Pacific, Atlantic and Indian Oceans. Whereas the effects are in phase between the Pacific and Indian Oceans, the Atlantic Ocean has a lag period of 12 to 18 months. ENSO is found to affect most of the developing countries dependent upon agricultural and fishery sectors for food, employment and foreign exchange. ENSO event occurred in 1982-1983 was a severe event, but the century's strongest El Niño happened in 1997-1998.

1.1.2 Indian Ocean Dipole (IOD)

IOD is a coupled ocean-atmosphere phenomenon which happens in the equatorial Indian Ocean (Fig. 1.3). It is characterized by anomalous cooling of sea surface in the south eastern equatorial Indian Ocean and anomalous warming in the western equatorial Indian Ocean (positive IOD). During IOD years, wind patterns change in the equatorial Indian Ocean from April-May and the dipole peaks in October. When a positive dipole is developing, the equatorial winds blow from east to west and the subsequent changes in the currents warms the oceanic waters along the Somali coast (Africa) favoring cloud formation, while the eastern seas around Indonesia becomes cooler and dry. This induces deepening of thermocline in the western Indian Ocean and shoaling in the east. During the negative dipole year, the features get reversed and the western Arabian Sea (near Africa) becomes cooler and less cloudy while the eastern Indian Ocean becomes warmer yielding heavy rains (around Indonesia).

IOD is developed due to the high SST gradient between the western equatorial Indian Ocean (50ºE – 70ºE and 10ºS – 10ºN) and the south eastern equatorial Indian Ocean (90ºE – 110ºE and 10ºS – equator). This gradient is named as Dipole Mode Index (DMI; Saji *et al.*, 1999). When DMI is positive, the phenomenon is referred as positive IOD and vice versa. IOD significantly influences the climate signals like Indian summer monsoon, Southern Oscillation Index (SOI), summer air temperature of Japan and the rainfall of Australia.

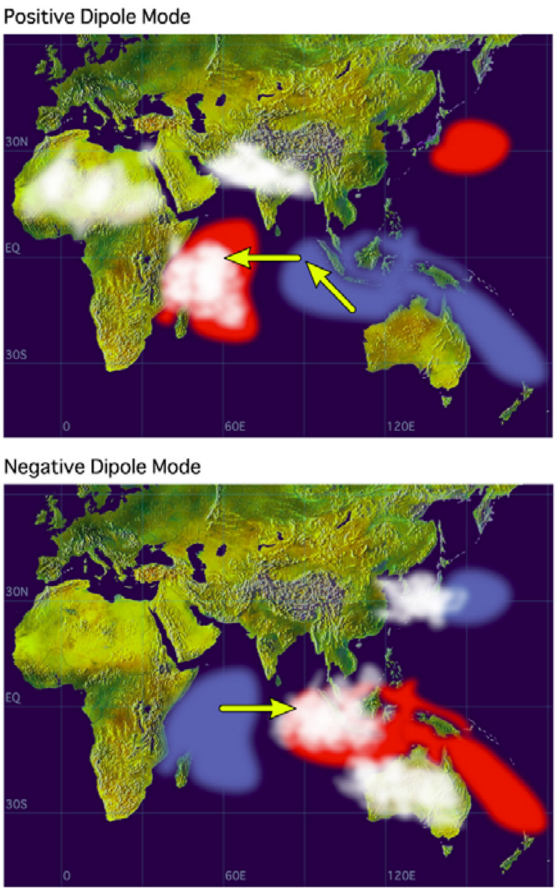


Fig. 1.3 Positive and Negative IOD events. Red (blue) contours indicate the presence of warm (cold) water mass. The wind stress is indicated by the yellow arrows. Areas of high precipitation are shown as white patches. Source: http://www.jamstec.go.jp /frsgc/research/d1/iod/.

Since the IOD affects the Indian summer monsoon it can also alter the influence of ENSO on Indian Summer Monsoon Rainfall (ISMR). A positive IOD has facilitated an excess rainfall over India during summer monsoon (1983, 1994 and 1997), even when there was a simultaneous occurrence of El Niño (Behera *et al*., 1999; Webster *et al*., 1999). When the IOD occurs in the absence of an El Niño or La Niña, it can strongly influence the rainfall as occurred in 1961 and 1994 (Saji *et al*., 1999; Ashok *et al*., 2001).

1.2 Ocean responses to climatic events

Many widely dispersed climatic extremes around the globe have been attributed to major climatic events. Major changes in oceans appear to be in the circulation pattern and other oceanic processes like upwelling. During an ENSO event, the oceanic condition of Pacific Ocean varies with respect to its strength. The upwelling off Peru coast, famous for anchovy fishery, is strong during normal years. But during El Niño years, the fishery of that region is very much affected by the increased water temperature and changed circulation pattern. The ENSO has its effects on the Indian Ocean also. During ENSO events, the SST variations are more in Indian Ocean. The interannual variability of SST in the Indian Ocean is a basin-wide warming associated with ENSO (Chambers *et al*., 1999; Behera *et al*., 2000; Chowdary and Gnanaseelan, 2007; Yoo *et al*., 2010). Arabian Sea also shows warming during ENSO years (Tourre and White, 1995). Major variability in the Indian Monsoon and in the sea level along Indian coastline are also reported during the ENSO years (Kirtman and Shukla, 2000; Srinivas *et al*., 2005).

The dipole mode of Indian Ocean changes the oceanic environment. In addition to temperature, the circulation pattern as well as upwelling features vary in Indian Ocean especially along the coasts of Indonesia and Africa. These bring in significant changes in the marine ecology and the long-term changes in fish populations; have also been associated with these climatic events. During IOD years there can be seen some oceanographic changes in Arabian Sea also.

1.3 Oceanographic variability and fish behaviour

The changes in oceanic environment have a profound influence on the aperiodic and seasonal migrations and occurrences of fishes. The recruitment, survival and growth of the fishes are also influenced by these aquatic environment changes. The environment also interferes with such biological activities as spawning and growth. Sea water temperature is the most easily determined environmental factor and in most cases the temperature may serve as a most useful indicator of the prevailing and changing ecological conditions. Besides temperature, the sea water salinity, waves, currents, light etc influence the survival of fish. Upwelling is a major oceanic phenomenon which also influences the pelagic fishery by enhancing the primary production of that region. Among the meteorological factors, rainfall has a key role in the survival of fishes. Many studies have been conducted along the west coast of India relating Oil sardine and Indian mackerel fishery and coastal oceanographic features (Sadananda Rao, 1973; Gopinathan, 1974; Murty, 1974).

1.3.1 Influence of Temperature

Water temperature is the most easily observed environmental factor, and therefore many studies have been done with sea water temperature, the fish behaviour and its fluctuations. The changes in water temperature are often cause simultaneous changes of other factors such as currents. In most cases the temperature may serve as a most useful indicator of the prevailing and changing ecological conditions. In the ocean, the temperature of the surface waters varies between +33° and -1.8°C. The depth of thermocline is an important factor in defining the hydrography and fishing potential. Fish prefer optimum combinations of physicochemical conditions in the environment. Nearly all fish stocks prefer specific temperature ranges. A precise knowledge of this optimum temperature is necessary for the prediction of fish availability. Measurement of SST can be used for predicting the abundance of a given fish stock (Ilmo and Taivo, 1961).

It is interesting to note that the best fishing grounds are frequently located on the boundary between two currents or in areas of upwelling and divergence. Surface shoals are also associated with seasonal changes in the surface temperature. The occurrence of the pelagic fish species depends largely on the vertical temperature structure (Murty, 1965). It is known, for example, that pelagic fish swim deeper when the surface waters are warm. Thus, the catches of many pelagic species are controlled by temperature (Madhupratap *et al.*, 1994). The lowest and highest temperatures at which a fish may survive depend upon its acclimatization. Therefore, sudden changes in the temperature are normally sensitive to fish than slow changes, which provide them time to get acclimatized. The long term temperature changes are not uniform in all oceans nor are they even similar in different parts of the same ocean. The changes are mostly determined by the changing patterns of major currents and regional meteorological conditions.

The sense of temperature in fish seems to be well developed. The fish species react to a change in water temperature of 0.03°C (Bull, 1952). Some studies states that fish select a certain temperature because of the effect of the same on their movement or activity (Sullivan, 1954; Freon *et al.*, 2005). The temperature change may act on fish as a nervous stimulus, as a modifier of metabolic processes and as a modifier of bodily activity. In fisheries the effects of temperature on fish manifest in a multitude of ways. As temperature affects bodily activity and mobility, low temperatures may affect the escape of fish from the gear and also the ability of fish to catch mobile food. The temperature may also bring about a difference in the regional distribution of juveniles and adults, as they often have different temperature tolerance and preferences (Alverson *et al.*, 1964; Qasim, 1973). They suggested that the upwelling seems to cause shoreward movement of fish.

The influence of water temperature on fish behaviour is most pronounced during spawning (Hodder, 1965). Every stock of fish has a normal temperature range, possibly with a seasonal cycle. At temperatures below this range the ripening of the sexual products is delayed and opposite in the case at higher temperatures. Temperature directly influences the rate of development and in conjunction with salinity, will determine the prevailing water density, thus affecting the buoyancy of eggs. The length of time taken for the incubation of eggs, as well as the length of larval life depends directly upon the temperature of the environment. The prevailing water temperature and currents during and after spawning are the most important factors determining the "brood strength" and survival of larvae of the commercially most important fish species (Kurita, 1959; Vivekanandan and Krishnakumar, 2010). There are several ways in which the temperature can influence the survival of larvae. The most important of these is probably its effect on the availability of food. It is evident that the availability of food suitable for larvae at the appropriate time is related to the phytoplankton production, which in turn is closely related to the seasonal changes of temperature and to the amount of light. Also the abundance of zooplankton (important as food for the larvae) is related to the abundance of phytoplankton and to the spawning period of adult planktonic animals, which again is controlled by temperature. In general, too high or too low temperature may put the development of larvae, so that larval development occurs before or after the peak population of the proper plankton. The rates of feeding, metabolism and growth are affected not only by the availability of food but also directly by the water temperature. It is frequently claimed that the fish grow larger and older at low temperature and that this is due to their lower metabolic rate and lower activity or sometimes to the greater availability of food.

According to Uda (1952) the best fishing area for tuna is in the contact zone of currents. The same applies to sardine, mackerel and flying fish. Surface catches were also associated with a seasonal latitudinal change in surface temperature. Many fishes make seasonal migrations towards the equator in winter. These migrations are either directly influenced by temperature or indirectly by the effect of temperature on the abundance of food. Apart from the seasonal migrations, the schooling connected with spawning, feeding etc must be controlled by temperature, either directly or indirectly. Dannevig (1955) pointed out that the mackerel in North European waters disappear from the surface when the water gets colder and appear again in the spring when the waters starts to warm up. In the higher latitudes the mackerel stay at a depth of several hundred meters during the winter. The migration to the surface starts in the spring when the bottom water becomes cool. The temperature also seems to affect the coastal-offshore distribution of some fishes. Mathews (1959) stated that mass mortalities can be caused by a change of 5°C in less than a few days. The long term temperature changes are not similar in all oceans and are determined by the changing patterns of major currents and local meteorological conditions. Taning (1953) summarized the probable ways in which a long-term temperature rise can influence the distribution of fish in northern hemisphere. Uda and Okamoto (1936) concluded that the fluctuation in the yield of sardine is related to long term changes in temperature.

1.3.2 Influence of Salinity

Salinity variations affect the osmotic regulations of fish and determine the buoyancy of pelagic eggs. The variation in salinity is relatively small in offshore areas, but in coastal areas these variations are larger due to river runoff. The relation between fish behaviour and salinity is not necessarily direct. The variations of salinity very often indicate the change in water masses or in their stability conditions.

1.3.3 Influence of Upwelling

Coastal upwelling is a physical process in which the cold nutrient rich sub surface waters are coming up by replacing the coastal waters offshore, which triggers the primary production of that region. This enhanced primary production (phytoplankton growth) leads to a higher secondary production (mesozooplankton) which is subsequently transferred to the tertiary production (fishery). These upwelling areas are the spawning grounds of many pelagic fishes such as oil sardine and mackerel. Especially, the spawning of sardines is closely related to the occurrence of upwelling. They shift their spawning location according to the shift in upwelling area.

The Arabian Sea is characterised by the most pronounced oxygen minimum layer which is found between 100-150 m depth. When the oxygen minimum layer starts to rise along the continental shelf, the seasonal upwelling tends to start. The fishes migrate in front of it into shallow water or rise in the surface layer. There is a zone in shallow water where mixing by tidal currents and waves keeps the water aerated and there will be high concentration of demersal fish at the seaward boundary of this zone. With the intensity of upwelling, this zone fluctuates back and forth. Seawards of the upwelling area observed a high basic organic production. A little further offshore, the pelagic fishes gather and feed on zooplanktons which develop if and when the upwelling has lasted about a month or more.

The offshore upwelling occurs in divergence zones or in the centres of cyclonic eddies. The upwelling in these zones is normally slow and raises the sub-surface oxygen minimum layer only slightly into the euphotic zone. Under normal conditions in the sea, the dissolved oxygen content of water does not become a limiting factor in the distribution of fish. A high basic organic production occurs in the upper upwelling layers, because the oxygen minimum layer is very rich in nutrients. Thus more oxygen is added into the water of the euphotic zone due to the oxygen production by the high phytoplankton standing crop. Zooplankton populations develop at the edges of this zone and pelagic fish migrate into the area for feeding. However, in some cases the oxygen might affect the behaviour of fish. Johansen and Krogh (1914) found that oxygen deficiency in the water plays a role as a retarding factor in the development of eggs. If a doldrum corresponds to the Centrum of the divergence area and the wind blows away from the area gets stronger, the rate of upwelling can be suddenly intensified and the oxygen replenishment apparently slowed down. In this case the oxygen minimum layer is brought close to the surface and mass mortality of fish may result.

1.3.4 Influence of waves and currents

The onshore-offshore movements of fish are affected by waves to a certain extent. Some species might be more sensitive to waves and marine noises than others. Advection is the most important factor causing local changes in the environmental properties of the sea. Fish can be expected to respond directly to those environmental changes which are brought about by currents. But it is difficult to observe directly the behaviour of fish in currents in the natural environment. Currents transport fish eggs and larvae from spawning areas to nursery grounds and from nursery grounds to feeding grounds. Also the migration of adult fish could be affected by a current and its distribution in its boundaries. The diurnal behaviour of fish might be affected by currents (especially by tidal currents). Some studies proved that tidal currents also affect the fishery (Tester, 1938). Several fishing methods rely on tidal currents.

The different species of fishes react differently to the currents. The fluctuations in landings and in the availability of different commercially important fish stocks are in relation to the anomalies of wind. Normally fishes would tend to remain in their particular water mass, but transference from one water mass to another may takes place as a result of the changes in environment. It could be assumed that one of the main factors affecting the year-to-year variations of the availability of fish on any given ground is the prevailing current affected by the year-to-year anomalies of winds. The highest concentrations of pelagic fishes are found in the actual frontal zones characterized by high gradients of various parameters.

1.4 Meteorological factors and fish behaviour

There exists a direct and indirect correlation between the climate, weather and the fish. The recruitment of young specimens to a fish stock is usually correlated to weather conditions during the spawning season. The availability of plankton as fish food is also determined by the meteorological conditions such as the amount of sunshine and prevailing wind conditions. The behaviour and accessibility of fish are determined by the environmental factors which in turn are directly influenced by the meteorological conditions. Rainfall is also an important factor that causes many changes in the spawning conditions and survival of fishes. Antony Raja (1973) established that the fluctuations in oil sardine catch are due to the oscillations in the annual recruitment of the juvenile broods which in turn appear to be linked up with variations in the intensity of the southwest monsoon. The relationship between rainfall and fishery is also reported by Jayaprakash (2002).

1.5 Seasonal up and down migrations of fish

Pelagic as well as demersal fishes undertake seasonal migrations. Usually they migrate into shallow waters during summer and into deep waters during winter. The major causative factor for the migration are temperature, light or seasonal migrations of available food. The seasonal vertical migrations result in seasonal changes in the productivity of fishes.

1.6 Major pelagic fishes of Indian coastline

India has a coastline of over 7500 km and an Exclusive Economic Zone (EEZ) of 2.02 million km^2 and it has large potential for capture fishery. Among a multi-species oriented fishery, the oil sardine (*Sardinella longiceps*) and the Indian mackerel (*Rastrelliger kanagurta*) form the mainstay of Indian pelagic fisheries along the southwest coast of India. So these two fishes are taken for the study. The characteristics of these species are mentioned below.

1.6.1 Oil sardine (*Sardinella longiceps*)

Indian oil sardine (Fig. 1.4) is a very important fish species, which contributes nearly 1/3 of the total marine fish production of India. It belongs to the family *Clupeidae* under the Class Teleostomi of the Subclass *Actinopterigii* and Order *Clupiformes.* This neretic-pelagic clupeoid fish occurs on both west and east coast of India and it is a shoaling species particularly for the west coast of India. The successful years of the oil sardine fishery bring as much prosperity to the fishing community and its failure cause a major economic arrest.

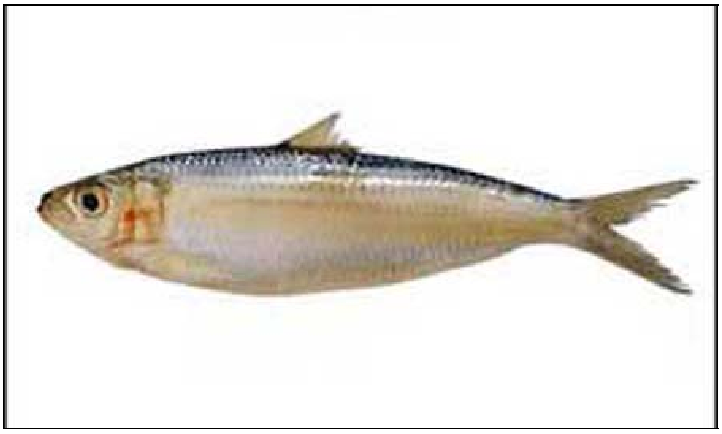


Fig. 1.4 Oil sardine (*Sardinella longiceps*)

The oil sardine has a general distribution from the Gulf of Oman along the Makhran coast of Pakistan, along the west coast of India around Sri Lanka, east coast of India approximately up to Vishakapatnam. The distribution of oil sardine occurs in massive shoals mainly along the southwest coast of India. Roughly the coast lying between 8^{o}N-16^{o}N represents the most intense concentration of oil sardine shoals and accounts for the bulk of the Indian catches. The area around 11^{o}N witnesses the densest shoaling of these species. Most of the shoals are captured almost from the shore line to an off shore depth of 15 m approximately. This roughly represents a belt of 12-15 km from the shore (Kumaran *et al.*, 1992).

The shoal starts appearing in the coastal waters in early June, but commercial fishing start from July to March with maximum intensity in October to January. During July-August period, juveniles appear along the coast and by September-December, they form a large proportion of the catch. By January-February the numbers of juveniles has been drastically reduced and mostly 1-yr and above age groups are taken. With the onset of pre-monsoon showers, the approximately 1-yr group enters the inshore with ripening gonads from approximately June. The spent resting adults will start appearing with the juveniles during January-February, disappear from the area during February-June and reenter with the virgin spawners for the second spawning. The main reason seems to be a gradual increase in temperature from south to north from September to May and this might induce the shoal to move in a northerly direction along the coast. Chidambaram (1950) found that the temperature of 26^{0}-28^{0}C is favorable for inshore migration of oil sardine, particularly the juveniles and he found that temperature over 29^{0}C during March to May causes the offshore disappearance of the adult fish. According to Nair (1959) the shoreward migration of the spawners during the monsoon season as well as the offshore migration into the deeper waters during the post monsoon months is for spawning purposes. The oil sardine shoals range from 2 – 25 m in length and 1 – 20 m in breadth; the speed is approximately 5 km per hour. The shoals congregate near the surface at sunset (Balan, 1962).

The spawning season of oil sardine extends from June to October with an intense activity of 2–3 months during this period, depending on the availability of favourable ecological conditions (Hornell and Nayudu, 1924; Devanesan, 1943). Nair (1959), also states that the spawning season of this fish is protracted extending into November with intense activity in August and September. The shoreward migration of the fish is for spawning with the stimulus given by the southwest monsoon. So there may be a slight shift in the spawning season due to the early or late onset of monsoon. The oil sardine spawns only once in its lifetime (Nair, 1959). Some workers pointed out that it may even spawn twice before the end of its fishable life-span (Antony Raja, 1967). The eggs of oil sardine are discharged in 3–4 batches during the spawning season (Dhulkhed, 1967). Oil sardine spawns generally at night and a few days before and after the new moon, there by suggesting a lunar periodicity in spawning (Devanesan and Chidambaram, 1943; Antony Raja, 1969). The spawning grounds of oil sardine are located beyond the coastal fishing zones. The oil sardine is a prolific breeder and is estimated to liberate about 70,000–80,000 eggs on an average (Devanesan, 1943; Devanesan and Chidambaram, 1948; Nair and Chidambaram, 1951; Nair, 1959).

On the basis of length frequency data, the oil sardine grows to length of 155–170 mm in one year and 190 mm in two years. Oil sardines attain their first maturity at the age of one year (Hornell and Nayudu, 1924; Devanesan, 1943; Chidambaram and Venkataraman, 1946; Qasim, 1973). From the analysis of landing data, it has been noted that 100-140 mm size (juveniles) group is the main mode, which contribute to the oil sardine fishery. The spawning takes place at the end of the first and second years of its life (Hornell and Naidu, 1924). From the absence of the older size-groups in the catches it was assumed that their life span was only 2.5 years. The maximum size group on record is 220–229 mm (Chidambaram, 1950; Rosa and Laevastu, 1960).

Oil sardine is predominantly a phytoplankton feeder. Among the important phytoplanktons, which the oil sardine feed on are (i) *Fragillaria oceanica (ii) Coscinodiscus (iii) Pleurosigma (iv) Dinoflagillates,* during summer months. Among these *Fragillaria oceanica* has been considered as one of the most favorite item and the significant correlation between its occurrence and oil sardine fishery has been reported (Nair, 1953). Also it has been suggested that the presence of *Fragillaria oceanica* in large numbers may be an indication of the abundance of the oil sardine in inshore waters. Copepods, dinoflagellates, ostracodes, larval prawns, larval bivalves, fish eggs, some algae, *Dinophycae* and *Trichodesmium* along with detritus have also been noted in the stomach contents of the oil sardine (Bal and Rao, 1984).

Bensam (1967) has stated that the juvenile oil sardines are mainly carnivorous in nature. They eat planktonic crustaceans like copepods, while adults are mostly phytoplankton feeders. The oil sardines avoid *Noctiluca* blooms. Also large quantities of flocculent muddy unrecognizable matter was found in the stomach of the oil sardines during October–December, exhibiting preference for bottom feeding (Hornell and Naidu, 1924). This bottom feeding habit could be only under unfavourable conditions near the surface (Devanesan, 1943).

Balan (1962) has made a detailed study on the shoaling behaviour of oil sardines. From the fishermen's report it appears that in highly turbid waters, highest catches (largest shoals) are to be encountered compared to clear water conditions. The discolouration of water is mainly due to turbulence, seems to have an attraction for shoaling oil sardines and during the months of September-October or even to November, when skies are overcast with dark cloud, the oil sardine shoals seem to be attracted towards the shore.

Nair and Chidambaram (1951), Panikkar (1952), Nair (1953) and Nair and Subrahmanyan (1955) were reported that the migration into offshore waters, heavy natural mortality, availability of the diatom (*Fragillaria oceanica*), and over fishing were the factors responsible for the fluctuations of the fishery. Antony Raja (1969) and Chidambaram (1950) have an opinion that the fishery is dependent on the success of spawning and the survival rate. Antony Raja (1969) found that the scanty rains in June–August of any particular year adversely affect the fishery of the following year. Main factors affecting the oil sardine fishery are

(i) Abundant blooms of *Fragillaria oceanica*, *Coscinodiscus* and *Pleurosigma* due to the upwelling of coastal waters with the onset of south west monsoon.

(ii) Minimum average rainfall of 30 mm daily for successful spawning

(iii) Water temperature not exceeding 26^{o}C for shoaling

(iv) Variations in the pattern of coastal current.

The chief crafts used for exploitation of oil sardines are Dugouts (Odam, Vanchi) and Canoes (Thoni) along Kerala coast and Out trigger boats along Karnataka and Maharashtra coast. The important gears used for capturing oil sardines are engulfing nets or boat seines (Mathikolivala, Pattenkolivala, Odam Vala, Paithuvalal), Shore seines (Rampani) and Gill nets—both drift & set gill nets (Mathichalavala). Among them Mathikolivala, Pattenkolivala, Rampani and Mathichalavala are important.

1.6.2 Indian mackerel (*Rastrelliger kanagurta*)

Indian mackerel is a pelagic scombroid fish widely distributed along Indian coast and is highly exploited (Fig. 1.5). It belongs to the genus, Rastrelliger under the family Scombridae, under Perciforms, of the sub-class *Actinopterigii* and class Teleostomi (Jordan and Starks, 1908). Out of different species, *Rastrelliger kanagurta* contributes the bulk of the commercial landings of Mackerel. It contributes around 15% or even higher to the total marine fish landings of India. Indian mackerel is widely distributed in the tropical regions of the Indian and Pacific Oceans between latitudes 30°N and 30°S and longitudes 30°E and 160°W. In the inshore waters up to 25 meters, it is well known to occur all the east and west coast of India.

Fig. 1.5 Indian mackerel (*Rastrelliger kanagurta*)

The mackerel shoals enter the inshore waters of the west coast of India quite regularly in the post-monsoon months every year. They migrate to inshore waters for feeding (Bhimachar and George, 1952). Hydrological and meteorological features seem to play a part in the migration of the shoals

(Pradhan and Gangadhara Reddy, 1962). Mackerel seems to have higher susceptibility to variations in temperature than to salinity. It tolerates low salinity levels (even upto 2.04 %). Low temperature, low salinity and low pH value of waters seemed to be favourable for good Mackerel fishery.

Mackerel recede from coastal waters during the southwest monsoon period for the purpose of spawning. The region between Vizhinjam and Cape Comorin off the southwest coast of India appears to be the spawning ground. The period of intensive spawning is from June to August with the commencement of spawning in March or even earlier. On the east coast the commencement of the spawning period is October-November coinciding with the onset of the northeast monsoon. Mackerel generally spawns during night time (Devanesan and John, 1940; Vijayaraghavan, 1962) and eggs of mackerel are pelagic. Most larvae of mackerel obtained from water depths of 30-80m in the shelf area between Cochin and Quilon.

The size of *Rastrelliger kanagurta* at maturity is 224 mm and all fish below that size are to be regarded as juveniles. The commercial fishery begins to exploit mackerel from about a size of 180 mm. Fish below this size is also caught in good numbers in some places. About 80-90% of fish in the commercial catch comes from size below 220 mm, which they attain in the first year of its life.

Mackerel is a surface feeder in the inshore waters and consumes both phytoplankton and zooplankton. The phytoplankton elements comprising the food are the diatoms. The zooplankton food items include the organisms like crustaceans which form the major portion, and with copepods in high percentage. They avoid the algal form *Trichodesmium erythraeum*. The fishing season starts very early, in August in the southern zone from Cape Comorin to Ponnani and lasts till February. In the Central zone from Ponnani to Mangalore also, the season starts at about the same time and lasts till

March-April. In the northern zone from Manglore to Ratnagiri, the fishery starts late by about October-November and lasts till March. Peak catches occur in October-November.

Different types of crafts and gears are used for Mackerel fishery. In Konkan, north Kanara and south Kanara, the chief gears used in the operation are shore seines (Rampani), gill net (Pattabale) and cast net (Pag). The types of fishing boat are Pandi, Hodi and Dhoni with or without out triggers. In Kerala boat seines (Odam vala, Paithua vala) Ayilakollivala, Thattumvala, Nonvala) shore seines (Karavala) and gill nets (Ayilachalavala) are operated with the help of degout canoes.

An examination of the region-wise landings of Mackerel shows that the production is the highest from Karnataka coast forming nearly 38% of the all India catch. Kerala ranks next with very high catches which in some years exceed those of Karnataka. Kerala and Karnataka together give about 72% of the total Mackerel production. Along the Goa coast Mackerel production is fairly high ranking third in the regional production with over 12% of the catches. Nearly 90% of Mackerel come from the west coast.

Many studies established that there is an inverse relationship between these two fisheries, the success of one inversely corresponding with that of the other (Nair and Chidambaram, 1951). A successful year of Mackerel fishery coincided with failure of oil sardine fishery and vice versa. But in true sense both are not competitors of food. Eventhough both species are omnivores, the adult Sardine feeds mainly on diatoms while the Mackerel is predominantly a zooplankton feeder. (Madhupratap *et al.,* 1994).

1.7 Area and Period of study

Eastern Arabian Sea between 0-25°N latitude and 65°E-78°E longitude has been selected as the area of study (Fig. 1.6). The oceanographic parameters were analysed from this region and southwest coast of India which includes coastal waters off Kerala, Karnataka, Goa were considered for the fishery data. The selected period for the study was from 1991 to 2008 (18 years), during which the occurrence of extreme climatic events was more.

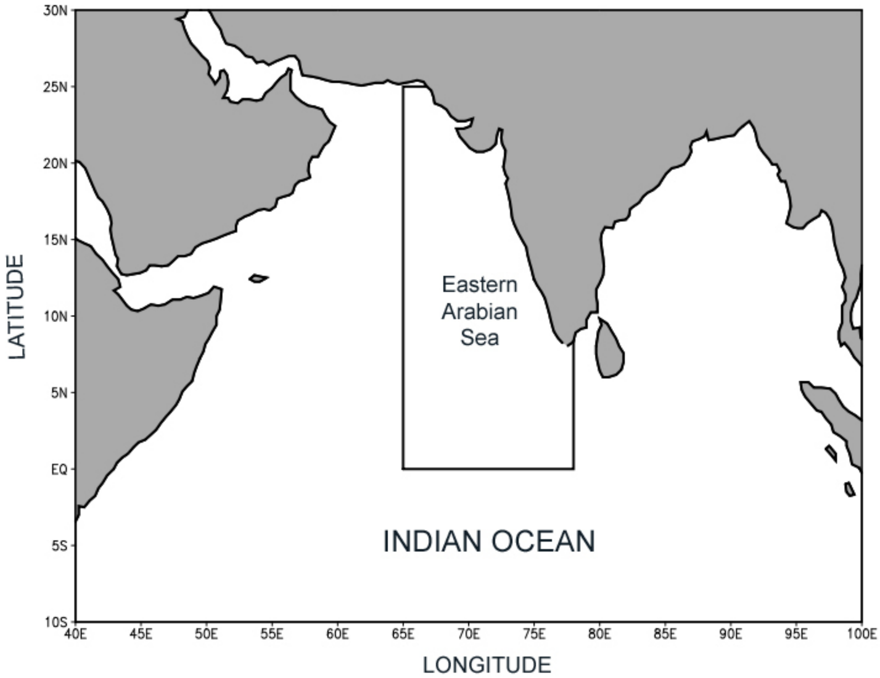


Fig. 1.6 Location map of study area

1.7.1 General Hydrography of the Arabian Sea

Out of five major oceans, Indian Ocean is the third largest of the world's oceanic division, which is in several respects, very different from other oceans. Indian Ocean extends from 20ºE - 147ºE longitude and 60ºS – 30ºN latitude, and it includes Andaman Sea, Arabian Sea, Bay of Bengal, Flores Sea, Great Australian Bight, Gulf of Aden, Gulf of Oman, Java Sea, Mozambique Channel, Persian Gulf, Red Sea, Savu Sea, Strait of Malacca, and Timor Sea. Among these, the Arabian Sea is a highly complex oceanic basin with strong physical forcing that leads to the changes in biological and chemical environments, especially during summer monsoon. The mixed layer shows significant seasonal variation to considerably influence the biological productivity. This basin, which forms the western flank of the north Indian Ocean, offers a striking example of wind-driven ocean circulation (Wyrtki, 1973a). The hydrographic characteristics of the Arabian Sea have been studied by many researchers (Sastry and De Souza, 1970, 1972; Wyrtki, 1973a; Colborn, 1975; Sharma, 1976a, b; Qasim, 1982; Swallow, 1984; Rao *et al.*, 1989; Shetye *et al.*, 1990; Bauer *et al.*, 1991; Brock *et al.*, 1992; Prasannakumar *et al.*, 2001; Naqvi *et al.*, 2003; Shankar *et al.*, 2005; Shenoi *et al*., 2005).

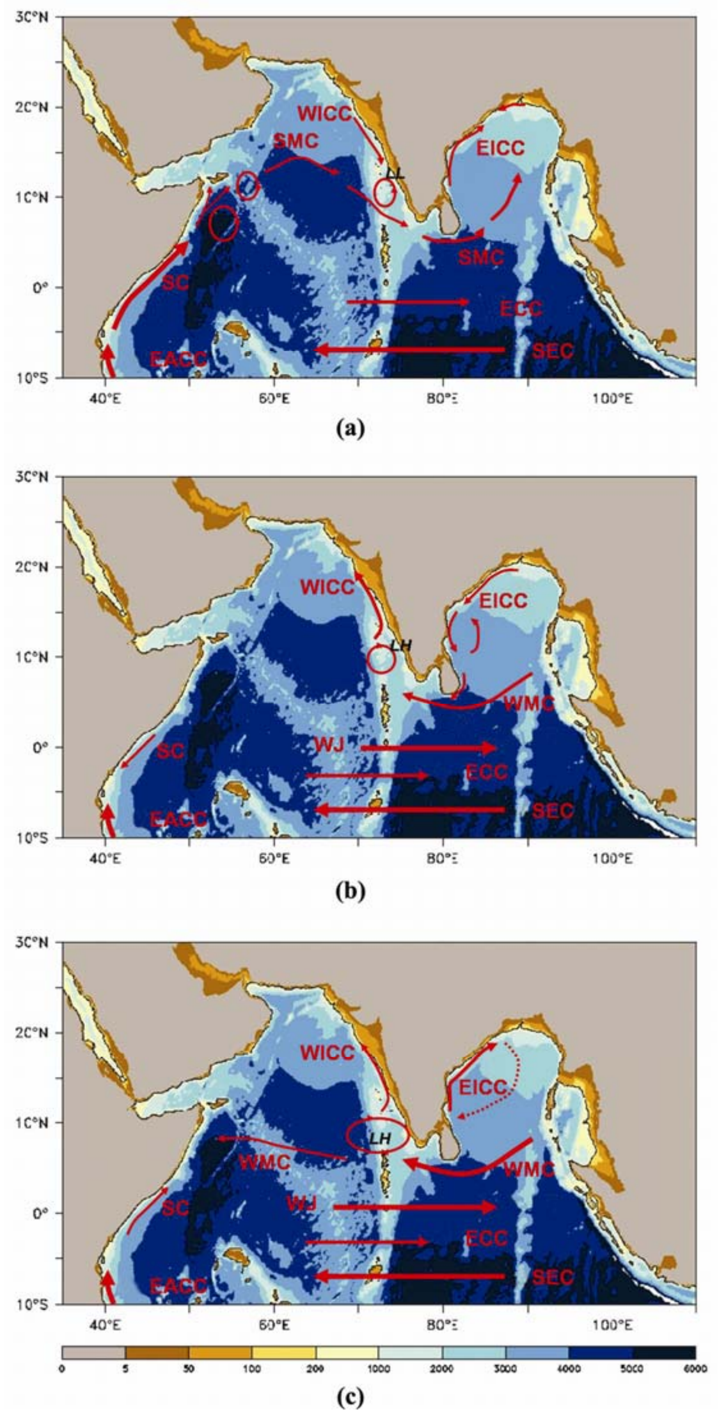
Among the world oceans, the Arabian Sea is found to one of the most productive systems due to a variety of physical processes associated with the monsoon cycle (Qasim, 1982; Banse, 1987). This results in two periods of increased biological activity, the southwest monsoon and northeast monsoon that occur in boreal summer and winter, respectively. During boreal summer, the winds are from southwest. The southeast trade winds from the south of the equator blow over the Arabian Sea as a strong southwesterly low-level j*et al*ong the Somali-Oman coasts, known as the Findlater jet (Findlater, 1977). These strong and steady winds during the southwest monsoon (Jun-Sep) generate coastal and oceanic upwelling zones and upward transport of great extent. Upwelling occurs mainly along the southwest coast of India, the east coasts of North Africa & Arabia. In all these regions, SST during this period is found to drop by a few degrees (Banse, 1972; Smith and Bottero, 1977; Swallow, 1984; De Sousa *et al.*, 1996).

The Arabian Sea undergoes dramatic changes in its circulation pattern following the monsoon climatology (Fig. 1.7). During summer monsoon, the circulation in the Arabian Sea is clockwise, as the Summer Monsoon Current (SMC) is fully developed during July and August (Shankar *et al.*, 2002). It weakens in September and by October (winter monsoon), the current direction and intensity become variable over most parts of the Arabian Sea.

Cutler and Swallow (1984) found that the SMC is eastward in the Arabian Sea. Wyrtki (1973a) inferred that the water movement in the Arabian Sea is from west to east during the southwest monsoon, whereas the surface current (~ 0.8 m/s) of central Arabian Sea is towards northeast with an average strength of about 0.8 m/s (Bauer *et al.*, 1992). The presence of a poleward undercurrent is indicated during the late southwest monsoon period (Muraleedharan *et al.*, 1995). A shallow equatorward current is also observed along the west coast of India during this time (Shetye and Shenoi, 1988). Along the eastern boundary of the Arabian Sea, the long shore component of the wind stress is generally equatorward and its magnitude is high near the southern end. The biological response of Arabian Sea is remarkable during southwest monsoon period, featuring intense phytoplankton blooms (Prasannakumar *et al.*, 2010). Coastal upwelling appears to be the dominant factor in maintaining the heat balance of the Arabian Sea. North of 15°N, the coastal upwelling is generally weak in the EAS (Banse, 1959; Naqvi *et al.*, 2000).

During boreal winter (Nov-Feb), the winds are northeasterly when the currents reverse (Varadachari and Sharma, 1967). Both the southwestward flowing Somali Current (SC) to the north of the equator and the northward flowing East African Coastal Current (EACC) to the south of the equator, change eastward and feed the Equatorial Counter Current (ECC) located just south of the equator (Kantha *et al.*, 2008). In the open Arabian Sea, the current direction is from east to west (Wyrtki, 1973b). During northeast monsoon season, in the South Eastern Arabian Sea (SEAS) centered at 10°N & 70°E), there develops a large anti-cyclonic eddy with a diameter of ~ 500-800 km in the upper 400 m (Bruce *et al.*, 1994). This feature, known as Laccadive High (LH), moves westward across the Southern Arabian Sea and dissipates in the mid basin during the intermonsoon period. At the same location a cyclonic eddy (Laccadive Low, (LL)) forms during early summer and propagates across the Southern Arabian Sea after a few months of its formation. The formation of these eddies are a consequence of westward propagating Rossby waves which are radiated by Kelvin waves propagating poleward along the western margin of the Indian Subcontinent (Shankar and Shetye, 1997). The northeast monsoon produces intense cooling and strong surface convection in the northern Arabian Sea favoring enhanced biological production (Madhupratap *et al.*, 1996). These highly productive periods are interrupted by the fall inter-monsoon and spring inter-monsoon during which, surface winds become relatively quiescent and the Arabian Sea relaxes towards a more tropical-subtropical oligotrophic character. Between the two monsoons (southwest and northeast), winds are westerlies along the equator and drive strong eastward-flowing surface jets along the equator known as Wyrtki-Yoshida Jets (Senan *et al.*, 2003). This peculiar monsoonal oscillation makes the Arabian Sea a unique region to study the response of surface currents on the pelagic ecosystem. Burkill *et al*. (1993) showed that the Arabian Sea is an oceanic basin hosting both eutrophic upwelling and oligotrophic downwelling environments. The open ocean temperature variations are influenced by variation in the Mixed Layer Depth (MLD) following density gradient or wind action. But, near the coast the physical conditions are changed due to upwelling. The most of the monsoon upwelling systems are located along the northwest coast of Arabian Sea, which supports high primary productivity and associated pelagic fishery (Longhurst, 1998). There is also an important upwelling region in EAS which is known for high biological production. Bhattathiri *et al*. (1996) recorded highest primary production (0.2 – 71.4 $mgCm^{-3}d^{-1}$) along the southwest coast of India during the summer monsoon. The southwest monsoon wind blows nearly parallel to the Arabian coastline causing the coastal upwelling due to Ekman transport (Swallow, 1984).

However, the open-ocean upwelling extends over wide area in response to positive wind stress curl (Prasannakuar *et al.*, 2001). By these upwelling processes, the euphotic zone is enriched by the nutrients from subsurface water (Sastry and De Souza, 1972; Smith and Bottero, 1977; Mantoura *et al*., 1993). As a consequence of this, the primary productivity increases in the northern Arabian Sea (Owens *et al*., 1993). Rochford (1964) provided the first description of the different water masses of the Arabian Sea based on the available hydrographic data. The three distinct water masses identified by Rochford originating in the northern Arabian Sea are, the Arabian Sea High-Salinity Watermass (ASHSW), the Persian Gulf Watermass (PGW), and the Red Sea Watermass (RSW). Subsequently, there have been a number of studies to understand the formation of Persian Gulf and Red Sea Watermasses and their spreading within the Arabian Sea in the context of circulation and hydrography (Varma *et al*., 1980; Premchand, 1981; Premchand *et al*., 1986; Sastry *et al*., 1986; Maillard and Soliman, 1986; Fedorov and Meschanov, 1988; Shapiro and Meschanov, 1991; Brock *et al*., 1992).



Colour scale represents the water depth

Fig. 1.7 Indian Ocean circulation during (a) summer monsoon (b) winter monsoon (c) Inter monsoon (Shankar *et al.*, 2002)

1.8 Scope of Study

For coastal countries the fishery resources are important for food security and as a source of income. Around 200 million people in developing countries rely directly or indirectly on fisheries. Particularly, communities in coastal regions depend upon these fishery resources. Still, the role of climatic variation in regulating marine fisheries is not well understood. Nowadays the frequency and intensity of climatic events are increasing, which is a major issue on climate change. So it is important to understand whether there is any impact of these climatic events on marine ecosystem, especially on fishes the vulnerability to climate change should be monitored and studied. Also it is very important to establish the functional relationships of ocean-atmospheric parameters with fishery. Systematic studies of fishery by incorporating the extreme climatic events along the southwest coast of India are scanty.

1.9 Objectives

a) To evaluate the impacts of extreme climatic events on oceanographic features of Eastern Arabian Sea.

b) To study variability of oil sardine and Mackerel fishery of southwest coast of India and to obtain a suitable statistical model, for its prediction.

c) To bring out the relationship of the observed variability of the fishery with the observed variability in the Eastern Arabian Sea, associated with extreme climatic events.

d) To predict the fishery based on statistical model and also with respect to the environmental parameters for the comparison.

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Chapter 2

LITERATURE REVIEW

The global climatic changes are associated with changes in the atmospheric and oceanic circulation in the tropical regions. A number of studies have been carried out to understand the climatic events and associated environmental variability all around the world. ENSO has been well recognized as the dominant signal of the interannual variability in the Pacific Ocean (Philander, 1990). The subsurface variability in the tropical Pacific Ocean plays a crucial role in the evolution of ENSO (Neelin *et al*., 1998). There are some studies which suggest that ENSO related warming takes place in the Indian Ocean as well (Tourre and White, 1997; Chambers *et al*., 1999; Yoo *et al*., 2010). The interannual variability of SST in the tropical Indian Ocean is a basin-wide warming associated with the ENSO (Nicholls, 1989; Tourre and White, 1995; Behera *et al*., 2000; Venzke *et al*., 2000). Meyers (1996) studied the SST variations of the Indonesian Throughflow and found ENSO signals. He concluded that remote forcing by the western Pacific zonal wind causes interannual temperature variations on the Australian side. He also observed that equatorial zonal winds in the eastern Indian Ocean were forcing the thermocline variations near Java.

In contrast to this, Saji *et al*.(1999) and Webster *et al*.(1999) have reported that the anomalous conditions in the Indian Ocean during certain years are independent of ENSO. A dipole mode exists in the tropical Indian Ocean characterized by warm SST anomalies in the western Indian Ocean and cold SST anomalies in the eastern Indian Ocean in its positive phase. Saji *et al*. (1999) reflected this mode as IOD. This is an important finding on tropical Indian Ocean variability. They found that the SST anomalies are accompanied by easterly winds in the equatorial Indian Ocean and upwelling favorable alongshore winds off Sumatra. The wind anomalies alter the thermal structure of the equatorial Indian Ocean which is sustained for a long period as coupled air-sea interactions. They further showed that the dipole mode was phase-locked with seasonal cycles in the Indian Ocean and the maximum anomalies generally occured during boreal fall (October). Both atmosphere and oceans are affected by this dipole mode.

A number of studies have discussed the SST variability in tropical Indian Ocean during extreme climatic events (Nicholls, 1989; Saji *et al*., 1999; Webster *et al*., 1999; Behera *et al*., 1999; Murtugudde *et al*., 2000; Iizuka *et al*., 2000; Behera *et al*., 2000; Venzke *et al*., 2000; Behera *et al*., 2008; Sukresno, 2010). However, the link between surface and subsurface variations of the tropical Indian Ocean is still not clear. Very few studies have described the subsurface variability of tropical Indian Ocean (Tourre and White, 1995; Meyers, 1996; Murtugudde and Busalacchi, 1999; Schiller *et al*., 2000; Rao and Behera, 2005; Sun *et al*., 2010). Schiller *et al*. (2000) concluded that ENSO related subsurface signals are absent in the central Indian Ocean. Using Ocean General Circulation Model (OGCM), Murtugudde and Busalacchi (1999) reported a quasi-biennial oscillation in the thermocline depths of the southern tropical Indian Ocean, which is well correlated with the Somali jet. Rao *et al*. (2002) investigated the interannual variability in temperature of the subsurface tropical Indian Ocean based on the IOD. They compared the quasi-biennial behaviour of the tropical Indian Ocean and the interaction between subsurface and surface dipoles and found that in contrast to the SST variability dominated by ENSO, the subsurface variability is governed by the IOD. Gnanaseelan and Vaid (2010) provide the evidence of internal dynamics in the IOD formation. They explained about the positive trend in the downwelling Rossby wave and its contribution to the Indian Ocean warming.

Some investigations have shown that the sea surface height (SSH) also changes during dipole events. Chambers *et al*. (1999) found that the SSH remained low in the east and high in the west during a positive dipole mode event. This pattern reverses during the negative dipole mode which, however, is much weaker than the positive phase. Analysis of SSH anomalies from TOPEX/Poseidon suggests that westward propagating Rossby waves also cause warming of this region. The strongest positive dipole occurred during 1997-1998, coincided with the most intense ENSO of recent decades (Webster *et al.*, 1999). During that event, the SST in the eastern Indian Ocean was cooler by more than 2°C, while the western Indian Ocean was warmer by more than 2°C (Yu and Reinecker, 1999; Webster *et al*., 1999). Murtugudde *et al*. (2000) established that the anomalous easterlies produce the eastward Kelvin waves that lift the thermocline in the eastern Indian Ocean and the longshore winds off Sumatra enhances the cooling in the eastern Indian Ocean. They also found that warming of the western Indian Ocean was due to the weak southwest monsoon winds and the meridional advection sustained until early 1998 by the downwelling Rossby wave. Murtugudde *et al.* (1999) have brought out the link between primary productivity and dipole mode. There was a phytoplankton bloom in the eastern equatorial Indian Ocean off the coast of Sumatra during that event. Yu and Reinecker (2000) noticed that the southeasterly winds in the southern tropical Indian Ocean were deflected towards the equator, and the consequent reduction in latent heat flux was responsible for the warming of the southwestern Indian Ocean. Vaid *et al*. (2008) studied the twin gyre structure of equatorial Indian Ocean during IOD years by using the SSH. The anomalous wind stress curl during the IOD years was found to drag the annual Rossby waves from 78°E to 88°E. They also reported that the downwelling favourable wind stress curl deepens the thermocline to increase the SST and Sea Surface Height Anomaly (SSHA).

There was a positive dipole event during 1994 which was similar to that of 1997-1998, though weaker in magnitude. During that year the cold SST exceeded 1°C in the eastern Indian Ocean (Vinayachandran *et al*., 1999a). Reppin *et al*. (1999) showed that the wind pattern of equatorial Indian Ocean was unusual during 1994. i.e. instead of being westerlies during spring and fall, they were easterlies. As a result the eastward jets (Wyrtki, 1973b) in the equatorial Indian Ocean were very weak leading to shoaling of MLD and thermocline in the eastern part. During that period the strong winds off Sumatra were favorable for upwelling. Behera *et al*. (1999) noticed that the SST anomalies suppressed the convection over the eastern Indian Ocean. From Saji *et al* (1999) it can be seen that other significant positive dipole events since 1950 were in 1961, 1967, 1972 and 1982. They observed that the events of negative dipole also occur, but very little is known about them. Iizuka *et al*. (2000) recreated these dipole events in a coupled model. Vinayachandran *et al*. (2002) examined the seasonal evolution of the dipole mode events in the Indian Ocean by analyzing both surface and sub-surface signatures from the model and by comparing them with observations. The interaction between IOD and ENSO has been explained by Behera *et al*. (2006). Rao *et al*. (2007) discussed about the termination of IOD events using a coupled general circulation model. They observed a strong intraseasonal disturbances during July-August terminate the short-lived IOD events by triggering downwelling of equatorial Kelvin waves. During 2006 and 2007 boreal fall, two consecutive positive IOD events occurred associated with El Niño and La Niña conditions in the Pacific. These two positive IOD events had large climatic impacts, particularly in the Eastern Hemisphere (Luo *et al*., 2008). The evolution of the 2006 IOD was consistent with the large-scale

IOD dynamics, and had long-lead predictability owing to the oceanic subsurface memory in the South Indian Ocean. The 2007 IOD event, however, was rather weak and peculiar without a long memory indicating that the model has less predictability for weak events. The results show that seasonal climate anomalies in the Eastern Hemisphere associated with the two positive IOD events can be predicted 1–2 seasons ahead, which has potential societal benefits.

The climatic events ENSO and IOD have impacts on the rainfall and oceanic circulation. The impact of IOD on the interannual variability of Indian Summer Monsoon Rainfall (ISMR; Parthasarathy *et al*. 1994) showed that 78% of annual rainfall over India is during summer monsoon (June-September). Easterling *et al*. (2000) indicate that significant changes in rainfall have occurred during past decades in the south Asian monsoon region. During 1951- 2000, the frequency and intensity of monsoon rainfall events in central India showed a rising trend during 1950-2000 (Goswami *et al*., 2006).

Forecasting of the ISMR requires a proper understanding of forcings that modulate the Indian Monsoon. An important factor is El Niño (Sikka, 1980; Pant and Parthasarathy, 1981; Rasmusson and Carpenter, 1983; Webster *et al*., 1998; Yun *et al*., 2010), which weakens the ISMR to a large extent. There are many reports on the long-range forecasting over India (Krishnakumar *et al*., 1995; Pant and Rupa Kumar, 1997; Webster *et al*., 1998). Until the late 1980s, the El Niño influence on the ISMR was dominant, but afterwards, there has been an apparent decrease in its influence (Krishna Kumar *et al*., 1999; Kripalani and Kulkarni, 1999). The weakening of the ENSO–ISMR relationship is attributed the strong positive IOD events that can neutralize the ENSO (Slingo and Annamalai 2000; Ashok *et al*. 2001; Chang *et al*. 2001; Gershunov *et al*. 2001). This is because, the ISMR is positively correlated with DMI, whereas it is negatively correlated with the index that represents the ENSO phenomenon (Ashok *et al.*, 2001; Saji and Yamagata, 2003; Vinayachandran *et al.*, 2009).

Though there were intense ENSO events during 1990s, the ISMR remained normal. Saji *et al.* (1999) described that the IOD significantly influences the rainfall in the Indian Ocean rim countries. Ashok *et al.* (2001) reported an interdecadal changes complimenting between the ENSO-ISMR and IOD-ISMR relationships. The occurrence of IOD events is found to be the cause for the weakening of ISMR and ENSO relation. Ajayamohan and Rao (2008) established a relationship between extreme rainfall events and IOD in central India and found that these extreme rainfall events are modulated by the cool SST in the south equatorial Indian Ocean. In the last two decades, the instances of occurrence of such SST anomalies are more frequent over south equatorial Indian Ocean following the warming of the tropical Ocean. Raju *et al.* (2002) observed that warming western Indian Ocean during the positive IOD event modulates the ISMR. In the last decade, there were two strong positive IOD events; in 1994 and 1997 when the rainfall was very high. Behera *et al.* (1999) showed that the strong summer rainfall over India during 1994 was due to the cold SST anomaly off the coast of Indonesia formed during the intense positive IOD.

Ashok *et al.* (2001) and Behera *et al.* (1999) infer that IOD modulates a meridional circulation by inducing convergence/divergence patterns over Bay of Bengal during positive (negative) IOD events, leading to excessive/deficit monsoon rainfall over the monsoon trough region. Using an Atmospheric General Circulation Model (AGCM), IOD-induced convergence/divergence pattern over the Bay of Bengal was found to affect the ISMR Guan *et al.* (2003). In another study, Ashok *et al.* (2004) showed the importance of the IOD in modulating the rainfall over the northwest regions of India and in reducing the impact of ENSO on the summer rains. But Ashok *et al*. (2004) demonstrated that the positive IOD reduce the influence of the El Niño on ISMR. Bhaskar Rao *et al*. (2004) performed a simulation study of the 1994 monsoon over the Indian region. Gadgil *et al*. (2003, 2004) indicate that IOD's atmospheric variability with the ENSO explains most of the interannual variability of the ISMR. The circulation of Indian Ocean is also affected by these dipole mode events. The impact of IOD on surface currents however is unknown because there is no systematic monitoring system such as the 'Tropical Ocean Global Atmosphere (TOGA) – Tropical Atmosphere Ocean (TAO). Brown *et al*. (2008) have found that there is a zonal current variability, primarily along equator during IOD events.

Some studies illustrate that the IOD has various impacts on Arabian Sea also. In the Arabian Sea, the influence of IOD led to a decrease in chlorophyll *a* concentration, primary productivity and sea to air CO2 flux (Sarma, 2006). Chlorophyll *a* concentration in the western Indian Ocean and along the coast of India shows a decrease during the IOD years of 1997 and 2006 (Wiggert *et al*., 2006).

Since the marine fishery resources are important sources of income knowledge of the relation between these climatic changes and fish availability is very essential. The physical, chemical and biological oceanographic parameters are important in predicting and exploiting marine fishery resources. Correlations between these environmental variables and the spatial and temporal distribution of fish populations have been studied in different areas of the world (Hollowed and Wooster, 1992; Hollowed and Bailey, 1995; Hunter and Alheit, 1995; McClatchie *et al*., 2010). Climate fluctuations which drive changes in the marine environment have often found to bring interannual variability in abundance of fish populations (Sharp and

McLain, 1993; Parrish *et al*., 1983; Sharp, 1995). The changes in the physical properties of oceans may influence migration, recruitment, abundance and availability of fishes. These fluctuations in environmental conditions are responsible for the variations in fish stocks (Kawasaki *et al*., 1991; Mann and Lazier, 1991; Mann, 1992, 1993; Mann and Drinkwater, 1994; Polovina *et al*, 1995; Stenseth *et al*., 2002).

Long term variability in climate and hydrography of marine ecosystems leads to fluctuations in the abundance of exploited fish populations (Francis and Hare, 1994). Temperature is the most easily determined environmental factor. A lot of studies are carried out with establishing a relationship between SST and fluctuations in fish catch (Ilmo and Taivo, 1961; Oh *et al*., 2005). The life history of small pelagics (high mobility, plankton based food chains, short life span etc) are very sensitive to environmental changes. Its response to climatic variations can be quick, dramatic and are transmitted up in the food chain, affecting fish population (Hunter and Alheit, 1995).

There have been few attempts to relate pelagic fish catch from Indian waters to sea water temperature, salinity, rainfall, upwelling intensity, chlorophyll and so on, but with very limited success (Banse, 1959; Food and Agricultural Organization (FAO), 1980; Johannessen *et al*., 1981; Longhurst and Wooster, 1990; Madhupratap *et al*., 1994; Yohannan and Abdulrahiman, 1998; Jayaprakash, 2002). United Nations Development Programme (UNDP)/FAO Pelagic Fisheries Project (PFP) has done the work in coastal waters off southwest coast of India during 1971-1978 to establish a relationship between physical-biological parameters and pelagic fishery. The studies on hydrography along southwest coast of India, fish eggs and larvae studies and the environment on the major pelagic fishery (PFP, 1973; 1974; 1975; 1976) confirmed that “sardines spawn mainly in the near shore areas between latitudes 11° 30’ N and 15° 30’N. During the peak southwest monsoon, the concentrations of oil sardine larvae were observed in the central part of the southwest coast associated with upwelling. After the monsoon, they disperse and move closer to the coast, which becomes available to the shore based fishery, while the remaining stock thrives in the offshore on the shelf throughout the year".

The effect of sea water temperature and salinity on the availability of oil sardine and mackerel appear to be very significant (Suresh and Reddy, 1980). According to Blackburn (1965) and Nair and Muraleedharan (1993), thermocline would play a major role in the distribution and migration of tunas. However, long term impacts of oceanographic changes on pelagic fishery have not been reported from the Malabar Coast (southwest coast of India). Oil sardine and mackerel are the major pelagic fish species of southwest coast of India (Malabar Coast). Longhurst and Wooster (1990) found that the abundance of oil sardine (*Sardinella longiceps*) was highly variable on the decadal scale. Murty (1985) described the annual variations of the physical, chemical and biological characteristics of the waters and the pelagic fishery of the Kerala-Karnataka coast. Madhupratap *et al*. (1994) examined the chain of events leading to the productivity and their relation to the fishery. Madhupratap *et al*. (2001a) have made an attempt to address the seasonal and spatial variability in the west coast of India and their influence on fish composition and habits. They also speculated the productivity and its relation to fisheries in the Arabian Sea.

Jayaprakash (2002) analysed the fluctuations of a demersal fish, the Malabar sole and a pelagic fish, oil sardine in the Malabar upwelling ecosystem, in relation to long-term trends in rainfall, onset of monsoon and sea level. He reported that the fluctuations in abundance of oil sardine are clearly influenced by the trends in rainfall during southwest monsoon. Antony Raja (1973) made a forecasting of oil sardine fishery, by relating the annual oil sardine landings to summer monsoon rainfall data. A successful fishery can be predicted under a good but not excessive monsoon rainfall. Successful predictions of reduction in the harvest of juveniles have been made by Antony Raja (1967, 1969 and 1972) based on rainfall. Murty and Edelman (1970) also studied the relationship between the landings of oil sardine and the monsoon intensity. The trends in the oil sardine landings and the factors responsible for the fluctuations are discussed by Nair *et al*. (1973).

Malabar coast is one of the major upwelling systems of the world (Bakun *et al*., 1998). Upwelling is a major process that has many impacts on fishery. Many studies have been carried out by researchers on fishery and its relation with upwelling. The oscillation of the oxygen minimum zone off the Kerala-Karnataka coast and its spreading to shallow regions during upwelling have implications on demersal and pelagic fisheries (Murty, 1992). Krishnakumar and Bhat (2008) studied the seasonal and interannual variations in the oceanographic parameters and temporal pattern in upwelling off the Mangalore coast and their influences on the pelagic fishery. They also made an attempt to understand the influence of local and global environmental conditions on the alternating patterns of abundance between the Indian Mackerel and oil sardine from that area. The upwelling regions sustain high biological production. Chidambaram and Menon (1945) established that there is a positive correlation between the plankton and the pelagic fisheries during post monsoon period. Some researchers tried to connect the surface mixed layer with pelagic fishery. Hela and Laevastu (1962) showed that the pelagic shoals depend largely on the depth of MLD. MLD is also important for the vertical distributions of floating eggs and larvae of the pelagic fish (King and Hida, 1957; Silliman, 1950). Murty (1965) related MLD and thermocline along the west coast of India to the pelagic fishery. Krishnakumar and Bhat (2008) pointed out that the La Niña and El Nino events of 1997-1998 were responsible for the collapse of the mackerel fishery along the southwest coast of India. However, the oil sardine fishery revived during 1999-2000 because of its tolerance to El Niño/La Niña and the low predation by their eggs and larvae due to the collapse of mackerel population.

In the fishery management, reliable forecasts of catch are important for which, time series data is very essential. In many studies conducted earlier, the statistical methods have been effectively used for the analysis and forecast of fishery data. The time series analysis has been successfully applied to several cases (Jensen, 1976, 1985; Van winkle *et al.,* 1979; Mendelssohn, 1980; Saila *et al.*, 1980; Stocker and Hilborn, 1981; Sathianandan and Srinath, 1995). The application of various prediction models are applied in some of the recent studies (Pedraza-Garcia and Cubillos, 2008; Xu and Boyce, 2009). Xu and Boyce (2009) have studied the density dependence and environmental effects on Oil sardine off the Malabar coast. They emphasized that their results have important consequences for understanding catch variability and are potentially useful for facilitating management of this commercially important fishery.

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Chapter 3

MANIFESTATION OF EXTREME CLIMATIC EVENTS AND ASSOCIATED VARIABILITY OF OCEANOGRAPHIC PARAMETERS IN EASTERN ARABIAN SEA

3.1 Introduction

Global warming and associated climate change in the environmental parameters are the immediate threats to mankind and tropical regions are the most vulnerable to them. The climate change has major impact on the vulnerability of heavily populated coastal areas. Of the extreme climatic events, ENSO has been well recognized as the dominant mode of tropical climate variability. Several investigations suggest that ENSO related warming takes place in Indian Ocean, (Tourre and White, 1997; Chambers *et al*., 1999), although these anomalies are found to be comparatively weak in the Indian context. Studies demonstrated that the anomalous conditions occurred in Indian Ocean during certain years are independent of ENSO, but it is related to IOD. Also it is observed that, oceanography of North Indian Ocean has significant influence due to these extreme events.

According to International Panel for Climate Change (IPCC)'s assessment, the 'Climate Shift 1976-77' was associated with a phase change in the Pacific Decadal Oscillation (PDO) from negative to positive (Fig. 3.1) and with significant changes in ENSO evolution (Mantua *et al*., 1997; Zhang *et al*., 1997). These tropical climate decadal variations modulate the behaviour of ENSO with a shift towards more frequent, intense and long-lasting El Niños (Fedorov and Philander, 2000). From figure 3.1 it is clear that the ENSO shifted from predominantly cool phases to predominantly warm phases (El Niño) after 1977. The IOD events were also frequent after this climate shift. In this chapter the atmospheric as well as oceanographic variability including the seasonal processes of EAS during the significant IOD years for the period 1991-2008 has been explored. The parameters addressed include wind, temperature, salinity, heat flux, SSH, depth of 20degree isotherm, currents, upwelling index, primary productivity and rainfall.

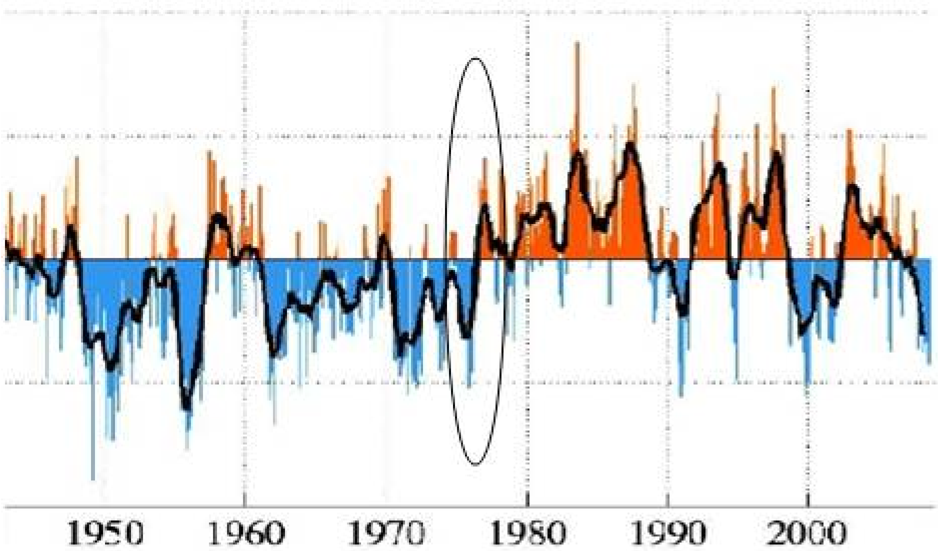


Fig. 3.1: 1976-77 Climate Shift- PDO index (http://jisao.washington.edu/pdo/)

3.2 Data and Methodology

DMI and Nino 3.4 index have been used to parameterize the IOD and ENSO events respectively. DMI is estimated as the difference between the average Sea Surface Temperature Anomaly (SSTA) in the western Indian Ocean (50°E – 70°E and 10°S – 10°N) and that in the eastern Indian Ocean (90°E – 110°E and 10°S – 0°), the two areas (Fig. 3.2) most affected by the IOD (Saji *et al.*, 1999; Vinaychandran *et al.*, 2002). National Centers for Environmental Prediction (NCEP) Reynolds Optimally Interpolated monthly

SSTA in 1°×1° resolution for the period 1991-2008 were used (Reynolds and Smith, 1994) for identifying the dipole structure. The estimation of DMI has been done with the SSTA. Nino 3.4 index is a measure of ENSO based on SST which is the area averaged SSTA over 5°S – 5°N, 170°W – 120°W (Trenberth, 1997). Occurrence of an El Niño (La Niña) event is identified from the 5-month running average of the Nino 3.4 SST index if it exceed (recede) 0.4°C (-0.4°C) for at least six consecutive months.

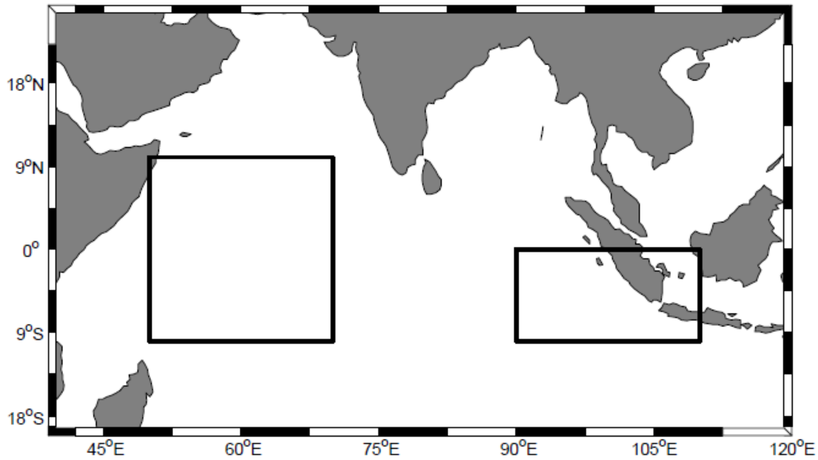


Fig. 3.2: Areas used for the estimation of DMI

The response of these extreme climatic events in the EAS in terms of interannual variability in SST for the period 1991-2008 is studied based on Advanced Very High Resolution Radiometer (AVHRR) derived SST. The 4 km AVHRR Pathfinder (version 5.0) developed by the University of Miami's Rosential School of Marine and Atmospheric Science (RSMAS) and the National Oceanographic Data Center (NODC) are used for this purpose (Kilpatrick *et al.*, 2001). The Conductivity–Temperature–Depth (CTD) derived temperature and salinity data sets collected from ten stations between the latitudes 5°N-15°N and 65°E-75°E longitudes by the National Institute of Oceanography Data Centre (NIODC) are used to study the vertical distribution. The vertical distributions of temperature and salinity in the month of September for the years 1992 and 1994 are analyzed here, which are the significant negative and positive IOD years. Monthly analysed mean of Sea Surface Salinity (SSS) for the four months representing each season of selected IOD years is taken from NODC (Levitus) World Ocean Atlas 1998 data base. The subsurface temperature and salinity used for this study have been derived from Simple Ocean Data Assimilation (SODA) product (Carton *et al*., 2005; Gnanaseelan and Vaid, 2010).

The measure of the changes of ocean heat content is part of the basic information needed for climate studies. It can be determined from vertical profiles of temperature by integrating them using the equation

$$H=\rho C_p \sum_{n=1}^{\infty} (T_n+T_{n+1})(D_{n+1}-D_n)/2$$ (Kurasawa *et al*., 1983)

Where T_n is the water temperature of the n^{th} standard depth D_n; ρ=1025 kg/m^3, the density of sea water and C_p =3850 J/kg/°C, the specific heat of sea water at constant pressure. In this study, the heat content of EAS in the upper 70 m layer for the period 1991-2008 has been calculated using the vertical data sets of temperature from the assimilated model output of SODA. The surface fluxes and downward-upward shortwave–long wave radiations are taken from Objectively Analyzed air-sea Fluxes (OAFlux) data sets. The data were daily averaged and linearly interpolated in 1°×1° grid.

The SSH and its anomaly are used to understand the planetary waves like coastal Kelvin, west ward propagating Rossby waves and the geostrophic flow pattern in the area. The data retrieved from Topography Experiment (TOPEX)/Poseidon Altimeter is used for the positive IOD years 1994, 1997 and for the negative IOD years 1996, 1998. Due to unavailability of SSH data during the year 1992, the data corresponding to the year 1998 has been considered which also represents a negative IOD year. Depth of 20 degree isotherm (D20) is a proper index for the thermocline variability and is also a good proxy for the pycnocline variability (Yu, 2003). The reanalysis data for D20 isotherm from European Center for Medium Range Weather Forecast (ECMWF) ORA-S3 (Ocean Re-Analysis System 3) in 1°×1° resolution is used in this study.

Monthly wind data from Scatterometer onboard the satellites European Remote Sensing (ERS) 1 and 2, was obtained from the Jet Propulsion Laboratory of Physical Oceanography-Distributed Active Archive Center (PO-DAAC), with a spatial resolution of 1°×1°. Geostrophic currents derived from Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO) altimetry and Niller climatology is also used in this study. The coastal upwelling index can be calculated from wind. Local Temperature Anomaly (LTA) is also used as upwelling index which is estimated by comparing the coastal and offshore SST (Wooster *et al*., 1976; Naidu *et al*., 1999; Smitha *et al*., 2008; Jayaram *et al*., 2010). Three locations are selected along the southwest coast of India between 8°N-13°N (Fig. 3.3) for estimating LTA. Since the influence of upwelling is known to extend up to 200-400 km from the coast towards west (Antony *et al*., 2002), in the present study the offshore stations are chosen at a distance of 3 degree longitude from the coastal stations.

$$LTA = T_{off} - T_{coast}$$

Where 'T_{off}' represents SST of offshore stations and 'T_{coast}' represents SST of coastal stations. The positive LTA values suggest coastal upwelling process.

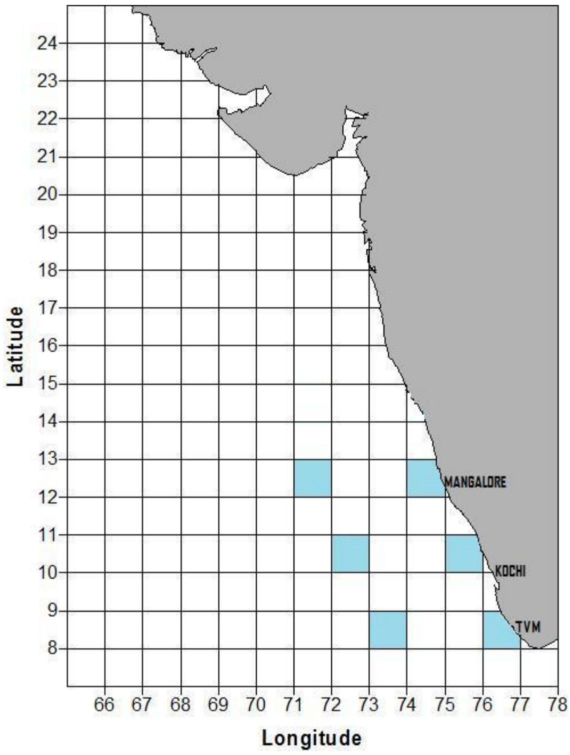


Fig. 3.3: Location map and grids (marked in blue) selected for the estimation of LTA

Sea viewing Wide Field of view Sensor (SeaWiFS) measured monthly composite chlorophyll *a* concentration of 9 × 9 km spatial resolution obtained from Goddard Space Flight Center (GSFC) of National Aeronautics and Space Administration (NASA) is used to study the productivity in the EAS during the IOD events of 1997 (positive) and 1998 (Negative). The analysis was conducted for six months (Sep-Feb). The years 1994 and 1996 could not be included because of the unavailability of chlorophyll *a* data.

To understand the spatial distribution of the impacts of IOD and ENSO on rainfall during 1991-2008, the precipitation data from Climate prediction center Merged Analysis of Precipitation (CMAP) in 1°×1° resolution has been used. The monthly summer monsoon rainfall data for

Kerala and coastal Karnataka based on rain gauge measurements of Indian Institute of Tropical Meteorology (IITM) have been used for this study.

3.3 Results and Discussion

3.3.1 The Climatic Events during 1991-2008

Frequency of intense climatic events was more during the study period 1991-2008 when compared to the past decades. The major positive IOD years were reported as 1994, 1997 and 2006 (Table 3.1). In addition the years 2007 and 2008 were also recorded as positive IOD years with low intensity. Among which 1994 was a prolonged positive IOD year (April-December) with its peak phase in October (Vinayachandran *et al*., 2002). But the strongest event was in 1997, in which the influence continued till the beginning of next year. This year also recorded with strongest El Niño of the Century. The ENSO years selected for the study period is listed in Table 3.2. A 'three in a row' positive IOD events were recorded during 2006, 2007 and 2008 of which the year 2006 was associated with El Niño and 2007 with La Niña. The years 1992, 1996 and 1998 were the strong negative IOD years during this period. Of these 1992 was associated with a weak El Niño and 1998 with a strong La Niña. The IOD of 1996 was followed by the La Niña of 1995-1996, which caused the low SST pattern of Arabian Sea during that year, rather than the other negative IOD years. Figure 3.4 shows the distribution of SSTA during significant positive and negative IOD events for the period 1991-2008. In the present study the positive events of the years 1994 and 1997 and negative events of 1992 and 1996 were only considered for further analysis. Since the data for geostrophic currents and SSH were missing for the negative IOD year 1992, the data pertaining to the other negative IOD year of 1998 has been used. Due to the unavailability of SeaWiFS chlorophyll *a* data for the years 1992 and 1994, the analysis on these parameters was done using the 1997 and 1998 data sets.

Table 3.1: Positive and Negative Dipole Mode events during 1991-2008

Positive IOD events	Negative IOD events
1994	1992
1997	1996
2006	
2007	1998
2008	

Table 3.2: El Niño and La Niña Events during 1991-2008

El Niño events	La Niña events
1991-1992	1995-1996
1992-1993	1998-1999•
1994-1995	1999-2000
1997-1998*	2000-2001
2002-2003	2007-2008•
2004-2005	
2006-2007	

Note: Underlined years represent significant (strong) IOD events; * represents strong El Niño year; • represents strong La Niña year.

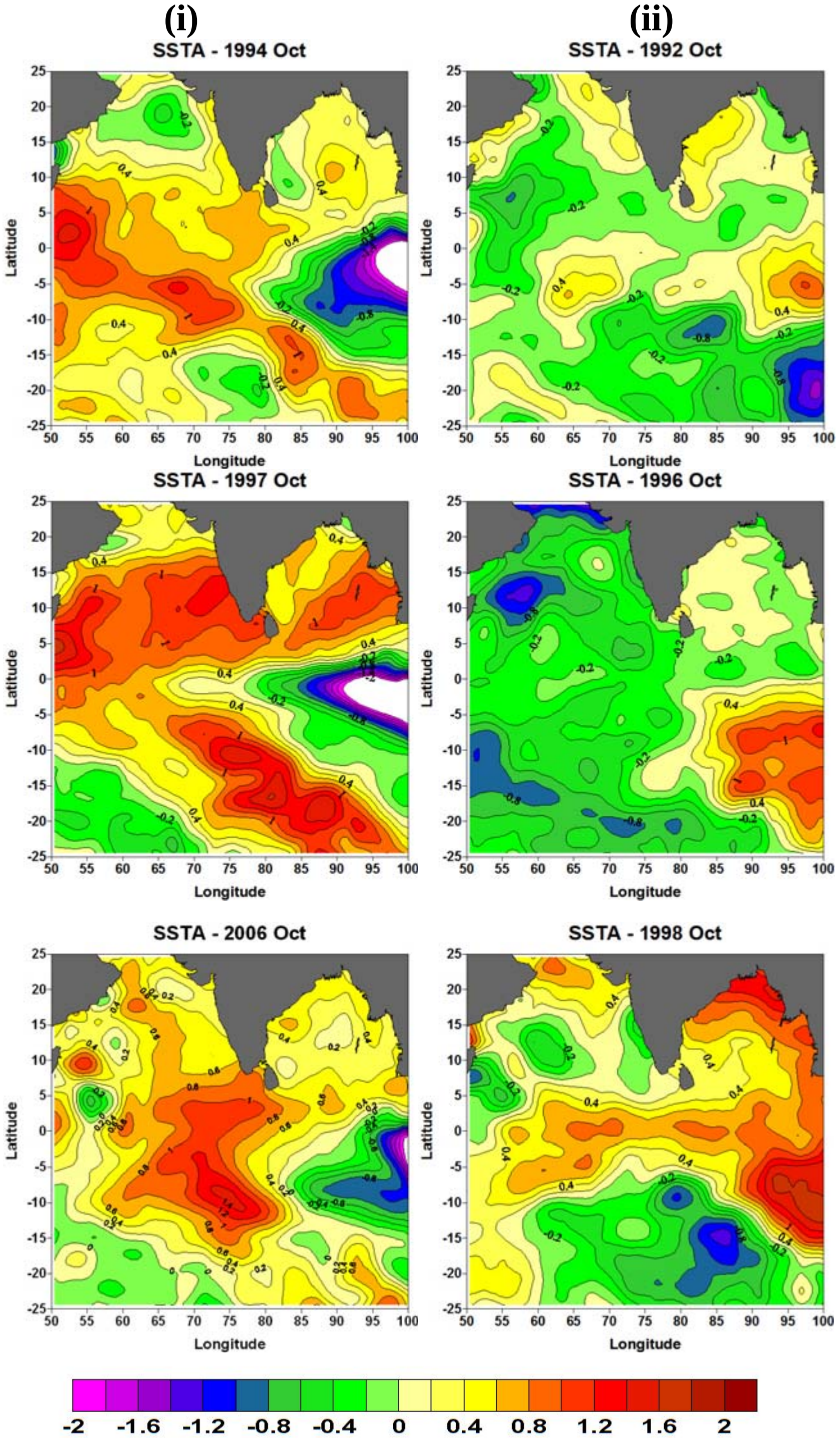


Fig. 3.4: The SSTA during significant IOD events in the month of October (Peak time) (i) Positive IOD events (ii) Negative IOD events

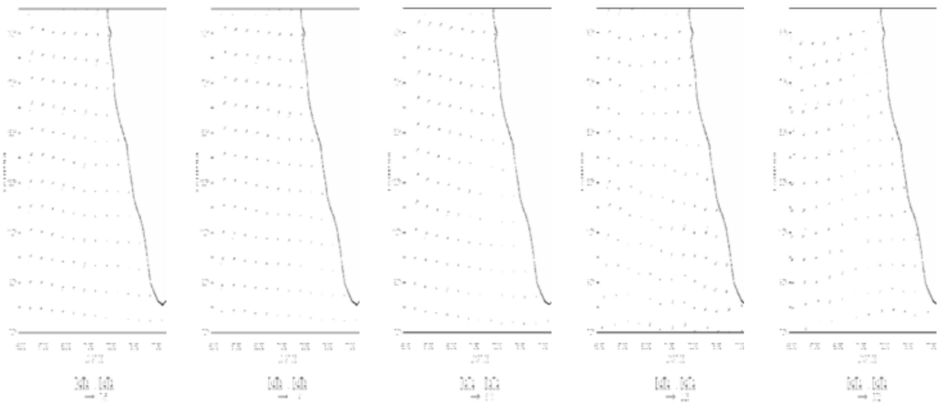
3.3.2 Variability in environmental parameters during extreme Climatic Events

3.3.2.1 Wind

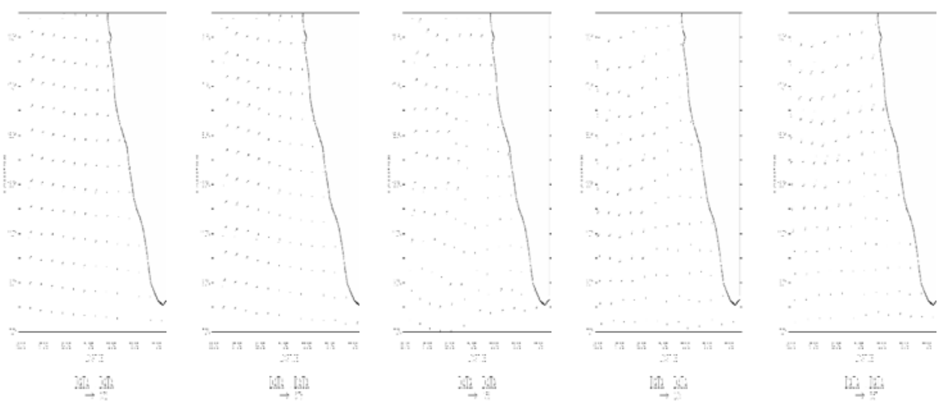
Seasonal reversal of the wind pattern over the north Indian Ocean causes the occurrence of different monsoons and seasonality in the environmental and oceanographic characteristic of the area. Along the coast wind forcing plays a major role in upwelling/downwelling phenomena. The modelling studies clearly revealed that the surface winds over the equatorial Indian Ocean plays an important role in modulating the circulation features of the northern Indian Ocean through remote effects (Potemra *et al*., 1991; Yu *et al*., 1991). During the IOD events, the wind patterns along the equator as well as in the north Indian Ocean show drastic changes. The climatology illustrates that the zonal winds are mostly westerly throughout the year with stronger magnitudes over the east central equatorial region. During the positive IOD regime, the equatorial westerlies are replaced by strong easterlies resulting in large negative Sea Surface Height Anomaly (SSHA) in the eastern Indian Ocean (Rao *et al*., 2009).

The present analysis shows that the wind pattern over the EAS is very responsive to IOD events. During the positive IOD years (Fig. 3.5a) the southwest wind pattern is fully developed in July and it sustained till September. In September, the south westerlies weakened and north easterlies are observed in SEAS. But all over the EAS except a small area in the southeast, the winds are south westerlies. In 1997 the winds are north easterlies in September all over the EAS, which is an IOD year with strongest El Niño. During October which is the peak phase of IOD, the reversal of wind occurs over SEAS from north easterlies to south westerlies. Whereas during the negative IOD years (Fig. 3.5b) the southwest winds are well developed in June itself and it sustain only upto July. The complete reversal of south westerlies to north easterlies occurs early in August.

Jun Jul Aug Sep Oct



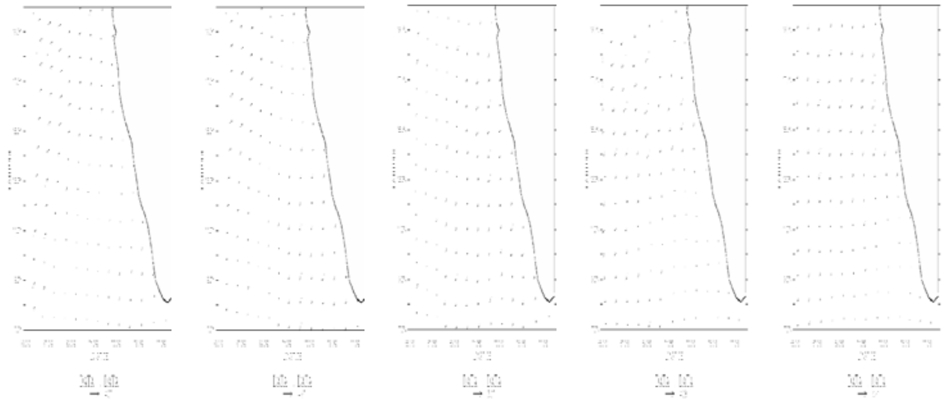
1994



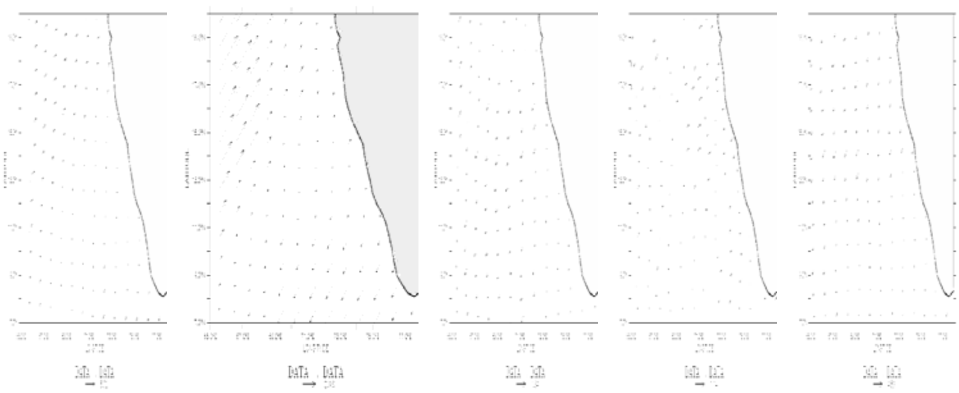
1997

Fig. 3.5a: Wind Pattern Over SEAS during southwest monsoon of positive IOD years 1994 and 1997

Jun Jul Aug Sep Oct



1996



1998

Fig. 3.5b: Wind Pattern Over SEAS during southwest monsoon of negative IOD years 1996 and 1998

3.3.2.2 Temperature

SST variations play a very important role in the meteorological as well as oceanographic processes as it undergoes large variations compared to other ocean parameters. The variability in SST is important as its duration and intensity provide the basis for studies related to climate change. The ocean-atmosphere interannual variability over the Indian Ocean basin received considerable attention in the last few decades (Schott and McCreary, 2001; Annamalai and Murtugudde, 2004a). Though several studies have come out explaining the teleconnection between ENSO and the interannual variability in Indian Ocean, the influence of IOD in regulating the oceanic processes in the region is scanty. Its signature in the Indian Ocean SSTs consists of a basin scale warming during El Niño and general cooling during La Niña conditions, predominantly during the spring season (Tourre and White, 1995). Nowadays, focus has been given to IOD and associated variability in SST (Bracco *et al*., 2006) over Indian Ocean. Here an attempt has been made to explain the interannual SST trends of EAS during 1991 to 2008 and the role of IOD in modulating the same.

Interannual variability in SST is studied in 2° latitude intervals along the coastal region. The sub-regionalization (8-10°N lat and 72-74°E long; 12-14°N lat and 72-74°E long; 16-18°N lat and 70-72°E long) has made in order to incorporate the latitudinal variability if any. Figure 3.6 shows the interannual SST variability for the three different locations of EAS for the period 1991 to 2008. All the three sub-regions show the same trend. During this period, there were three strong positive IOD years (1994, 1997 and 2006) and correspondingly there was an increasing trend in the SST. That means, after a strong positive IOD year, the SST is shooting up in EAS. 1997-98 was a strong El Niño year associated with a strong positive IOD. In that year the SST_{max} was greater than 31°C in EAS (Fig. 3.7). 1999-2000 was a strongest La Niña year and in that year SST showed an obvious decrease from the previous year. Three consecutive positive IOD events coming back to back is a rare occasion, which happened during the years 2006, 2007 and 2008. No such previous occurrences are detected in the historical SST records (*www.jamstec.go.jp/frcgc/research/d1/iod/*) and were not very strong. There was a weak El Niño during 2006-2007 and a strong La Niña in 2007-2008. Corresponding to this, SST showed an increase in 2007 and a decrease in 2008.

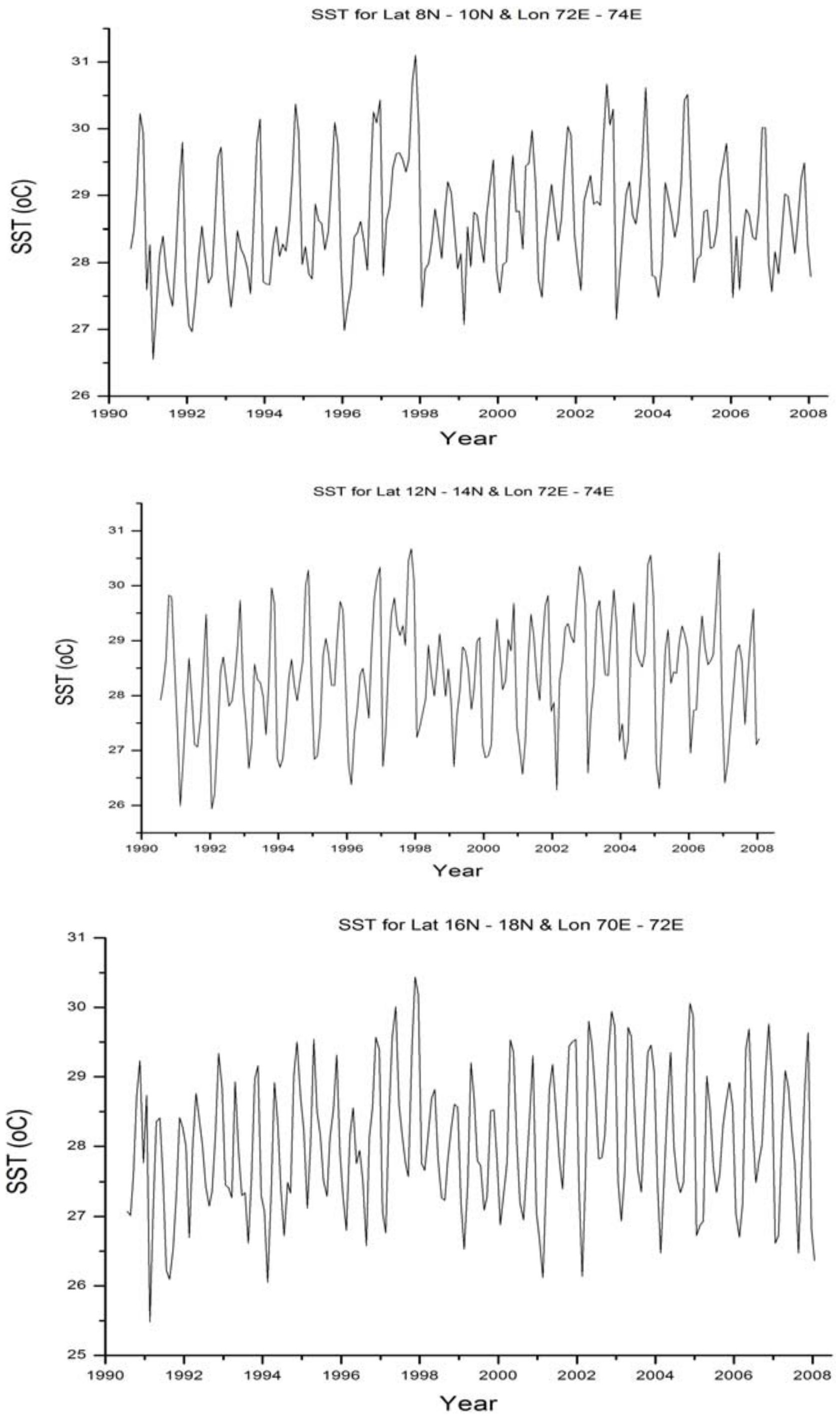


Fig. 3.6: Time series of SST for 3 different locations of EAS for the period 1991-2008

The variation of SST_{max} (April-May) for EAS is given in figure 3.7 which shows anomalous warming in the years followed by a positive IOD year.

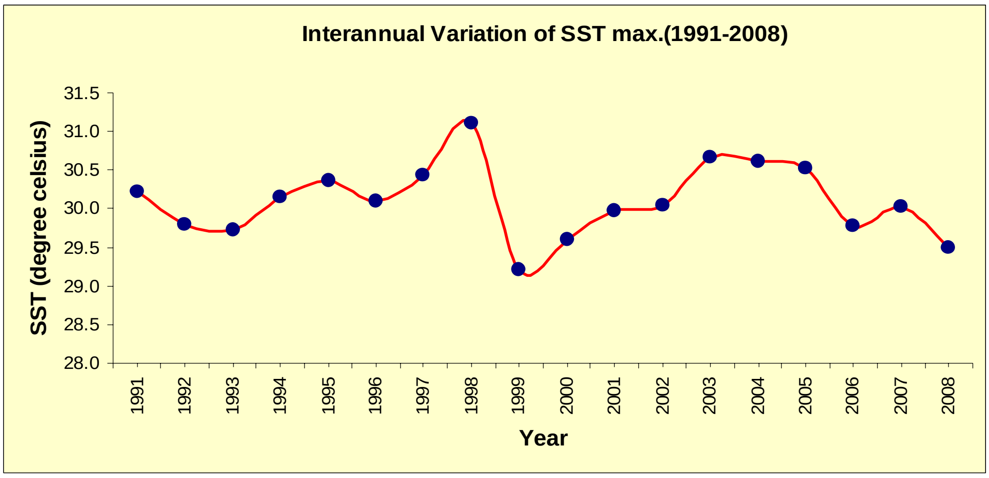


Fig. 3.7: Interannual SST_{max} variability of Eastern Arabian Sea (8-10°N lat and 72-74°E long) for the period 1991-2008

Figures 3.8a and 3.8b show the SSTA during different seasons of the positive and negative IOD years. During spring, the key oceanographic feature in the EAS is the occurrence of Arabian Sea warm pool (Hareeshkumar *et al.*,2008, Vinayachandran *et al.*, 2007) and it is clear from the figure that intense warm pool is observed associated with the positive IOD years as evidenced during the year 1997. Whereas negative IOD years are characterized by cold SSTA in EAS. Usually the summer monsoon is characterised by excessive cooling in the region especially due to enormous wind mixing and the prevalence of the coastal upwelling. But in positive IOD years there was a positive SSTA in EAS during this season when compared to the negative IOD years. The fall and winter seasons also show positive SSTA during positive IOD years. The maximum positive SSTA occurs during fall (October) which is the peak phase of IOD events.

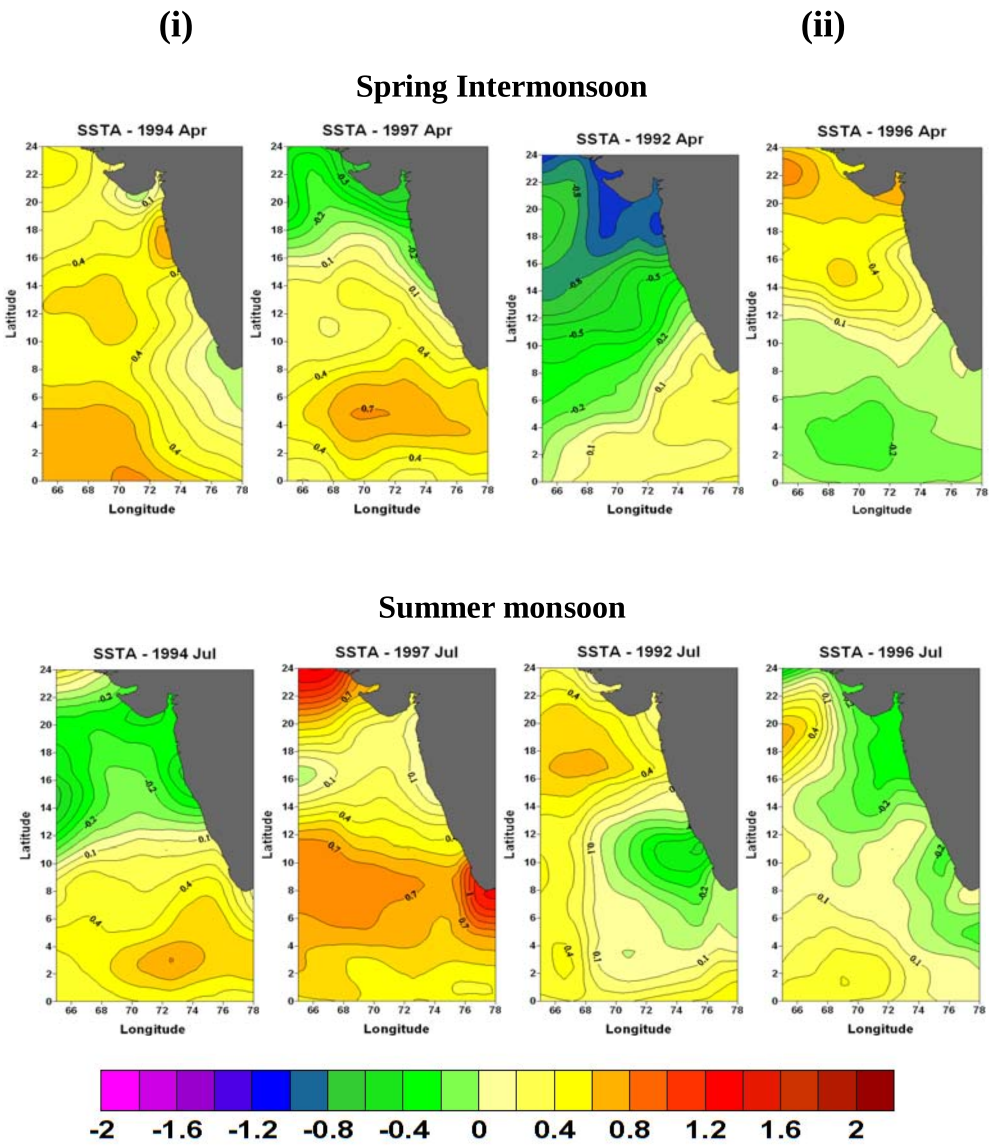


Fig. 3.8a: SST Anomaly of EAS for spring intermonsoon and summer monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

(i) **(ii)**

Fall Intermonsoon

Winter monsoon

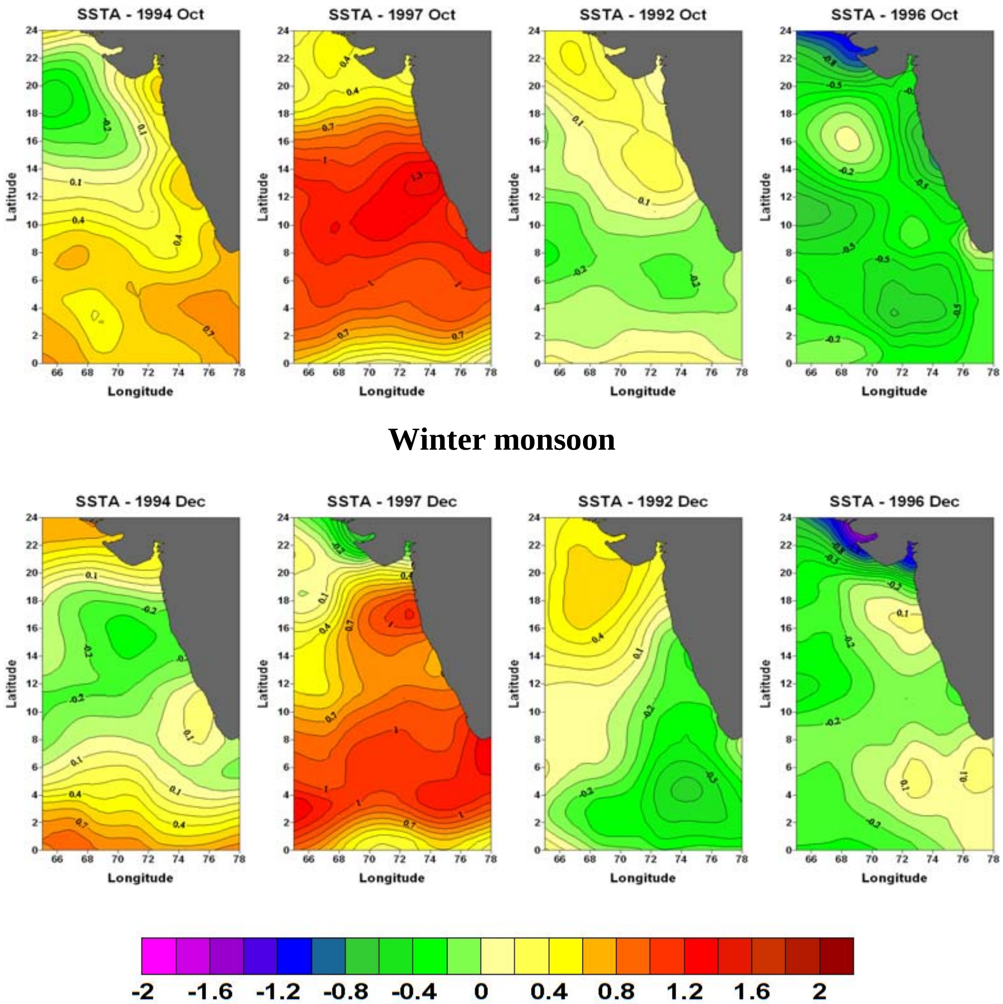


Fig. 3.8b: SST Anomaly of EAS for fall intermonsoon and winter monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

The vertical thermal structure (Fig. 3.9) of EAS shows that there is an increase in Isothermal Layer Depth (ILD) in the month of September during the positive IOD year (1994) when compared to the negative IOD year (1992). ILD during 1994 is 100m and for 1992 it is 80m. Since this month represents the summer monsoon period, the ILD can be approximated to MLD of that region. So it can be suggested that in EAS the MLD is deepening during the occurrence of a positive IOD. The deviation from the normal pattern of shallow MLD during 1994 September might be due to the domination of northeasterlies.

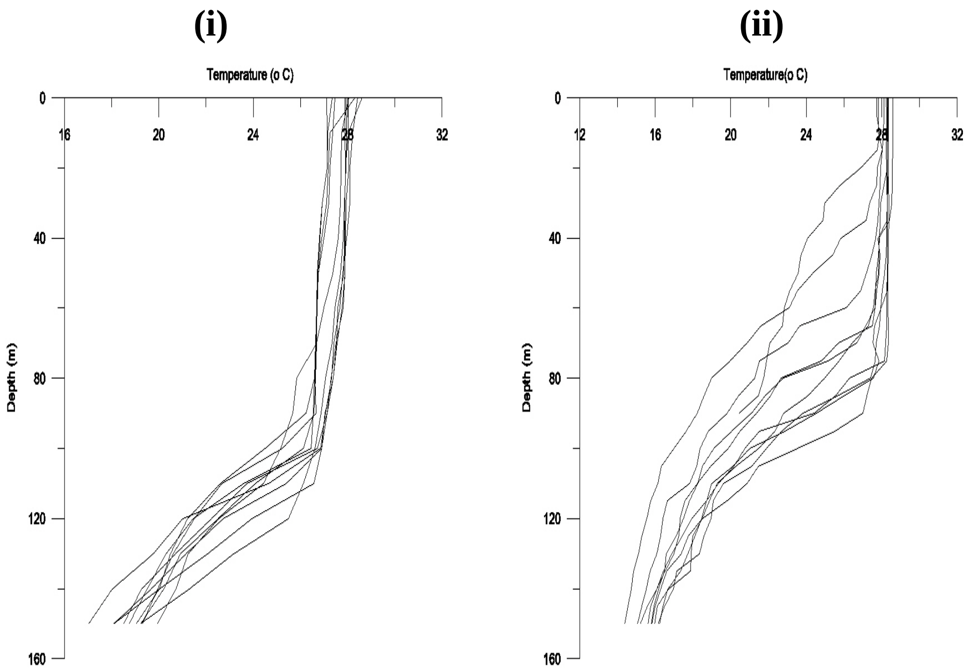


Fig. 3.9: Vertical distribution of temperature of EAS during September (i) 1994, the positive IOD year (ii) 1992, the negative IOD year

The subsurface temperature of EAS (25m depth) for four different seasons representing the positive and negative IOD years are shown in the figure 3.10a and figure 3.10b, which also highlights the variations in temperature during positive and negative IOD years.

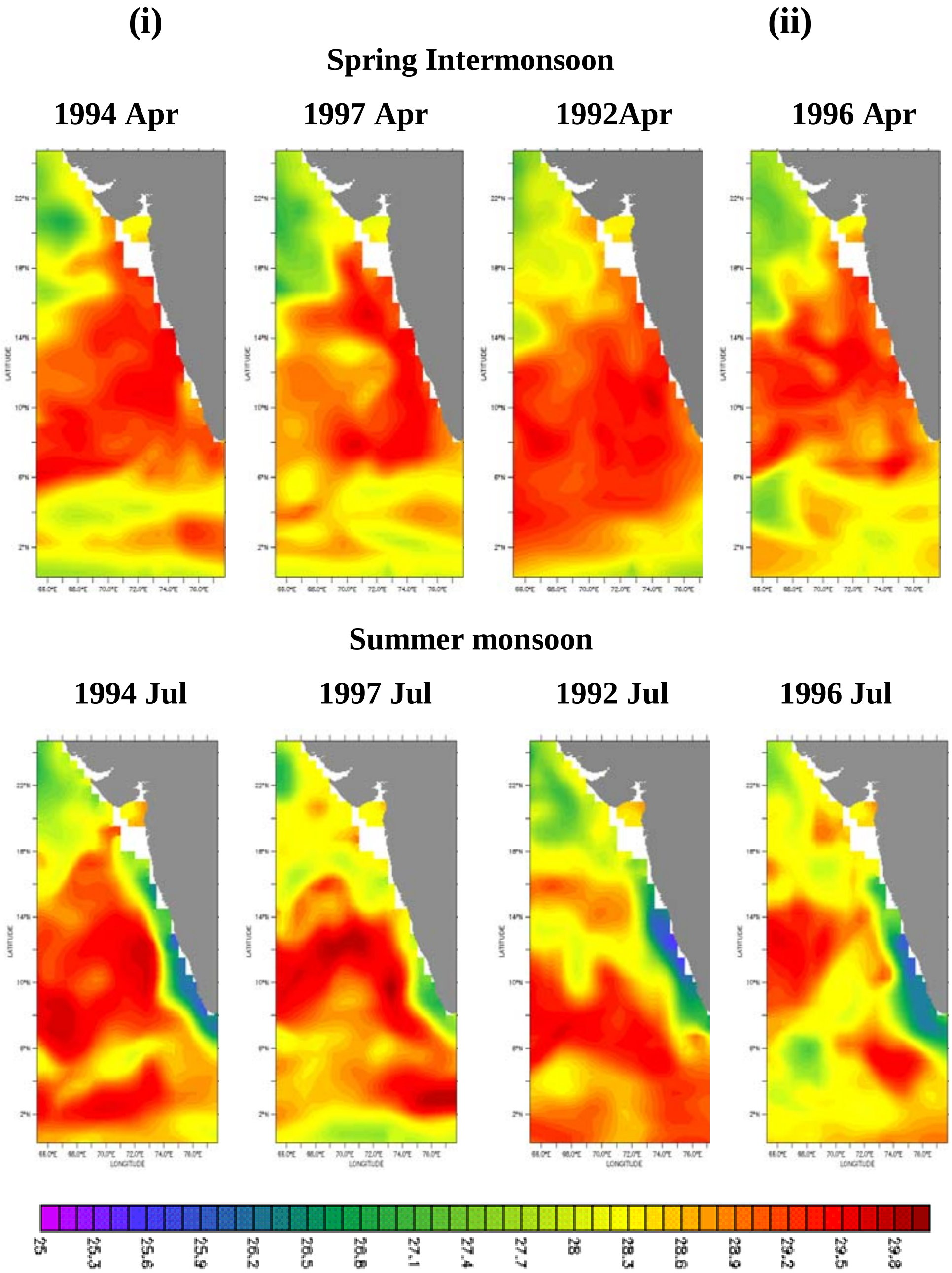


Fig. 3.10a: Subsurface Temperature of EAS at 25m depth for spring intermonsoon and summer monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

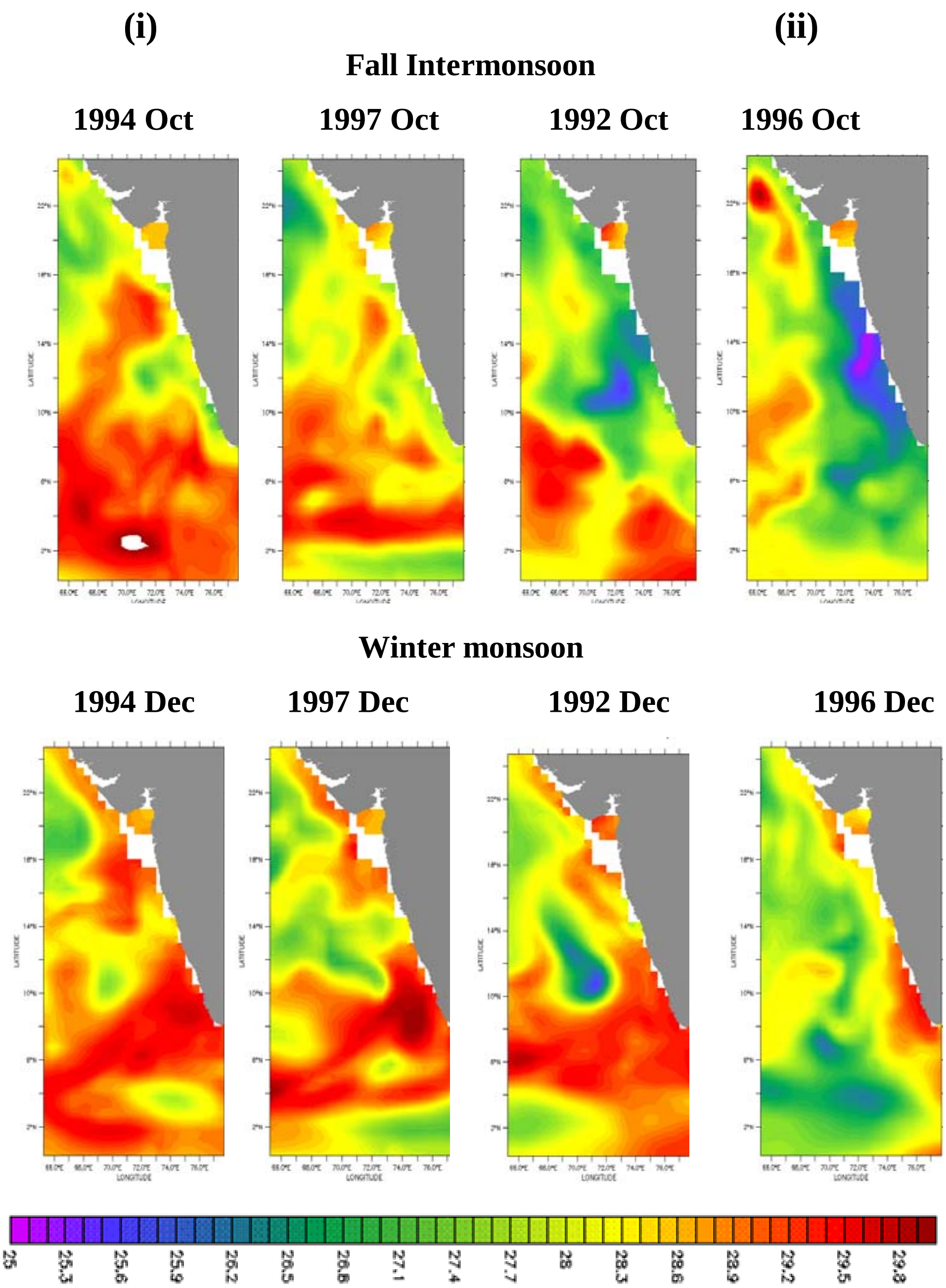


Fig. 3.10b: Subsurface Temperature of EAS at 25m depth for fall intermonsoon and winter monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

The heat content in the upper 70 m of EAS calculated for the period 1991-2008 shows the same trend with SST DMI (Fig. 3.11).

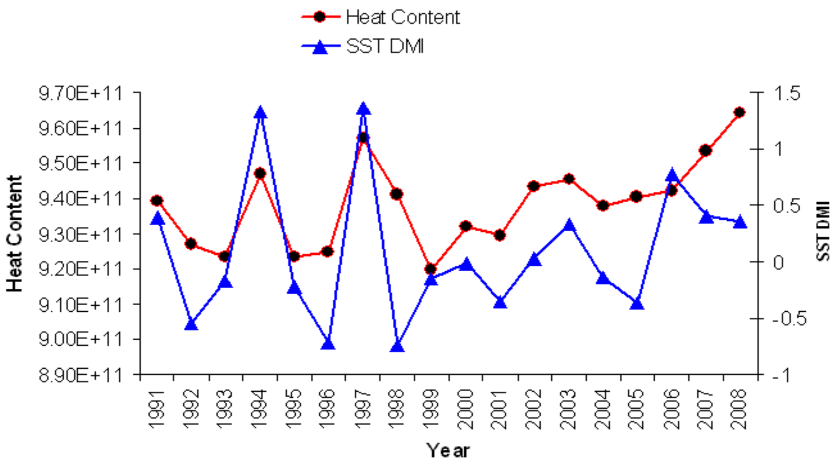


Fig. 3.11: Interannual variability of heat content (in Joules/m^2) of EAS (upper 70 m) with respect to SST DMI

3.3.2.3 Salinity

Salinity plays a major role in the near surface thermodynamics of tropical oceans because ocean's vertical stratification is dependent on salinity also (Sprintall and Tomczak, 1992; Murtugudde and Busalacchi, 1998). In the case of Arabian Sea, there is a high salinity due to the excess of evaporation than precipitation (Rao and Sivakumar, 2002) and in Bay of Bengal it is very low due to the enormous amount of freshwater discharge. The SSS distribution in the north Indian Ocean shows large spatial variability. During IOD years the salinity anomalies are high in eastern equatorial Indian Ocean (Perigaud *et al*., 2003; Masson *et al*., 2004). These salinity variations are also appeared in the southern part of EAS during IOD years, which are explained here. Figure 3.12a & b shows the SSS distribution during positive and negative IOD years for the four seasons. Vinayachandran and Nanjundiah (2009) showed that the Indian Ocean SSS anomalies are high only during the IOD years. These anomalies are about three times larger than that during non IOD and El Niño years. Masson *et al*. (2004) found that salinity effects reinforced oceanic anomalies and enhanced air–sea interaction favourable for the evolution of the 1997 IOD. In several places of tropical Indian Ocean, the salinity effects influence the MLD also. In North Indian Ocean the seasonally reversing monsoon currents transport low and high – salinity waters from their source regions and the horizontal SSS patterns are strongly influenced by ocean circulation (Schott and McCreary, 2001; Shankar *et al.*, 2002). The East India Coastal Current (EICC) carries low-salinity water from the river mouths into the southern Bay of Bengal (Shetye *et al.*, 1996; Vinayachandran *et al.*, 2005) and into the eastern Arabian Sea (Shetye *et al.*, 1991; Shenoi *et al.*, 2005; Kurian and Vinayachandran, 2007; Durnad *et al.*, 2007).

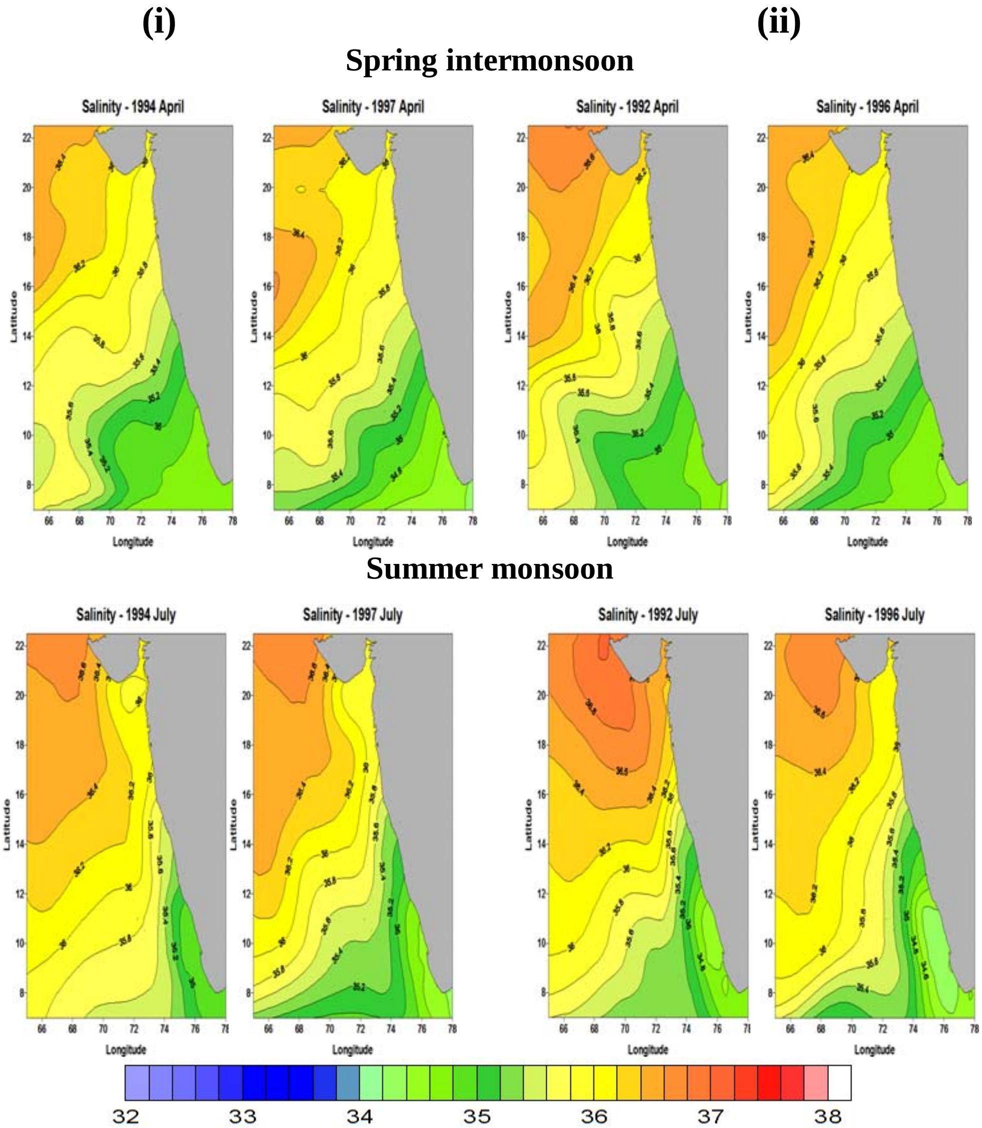


Fig. 3.12a: SSS of EAS in spring and summer monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

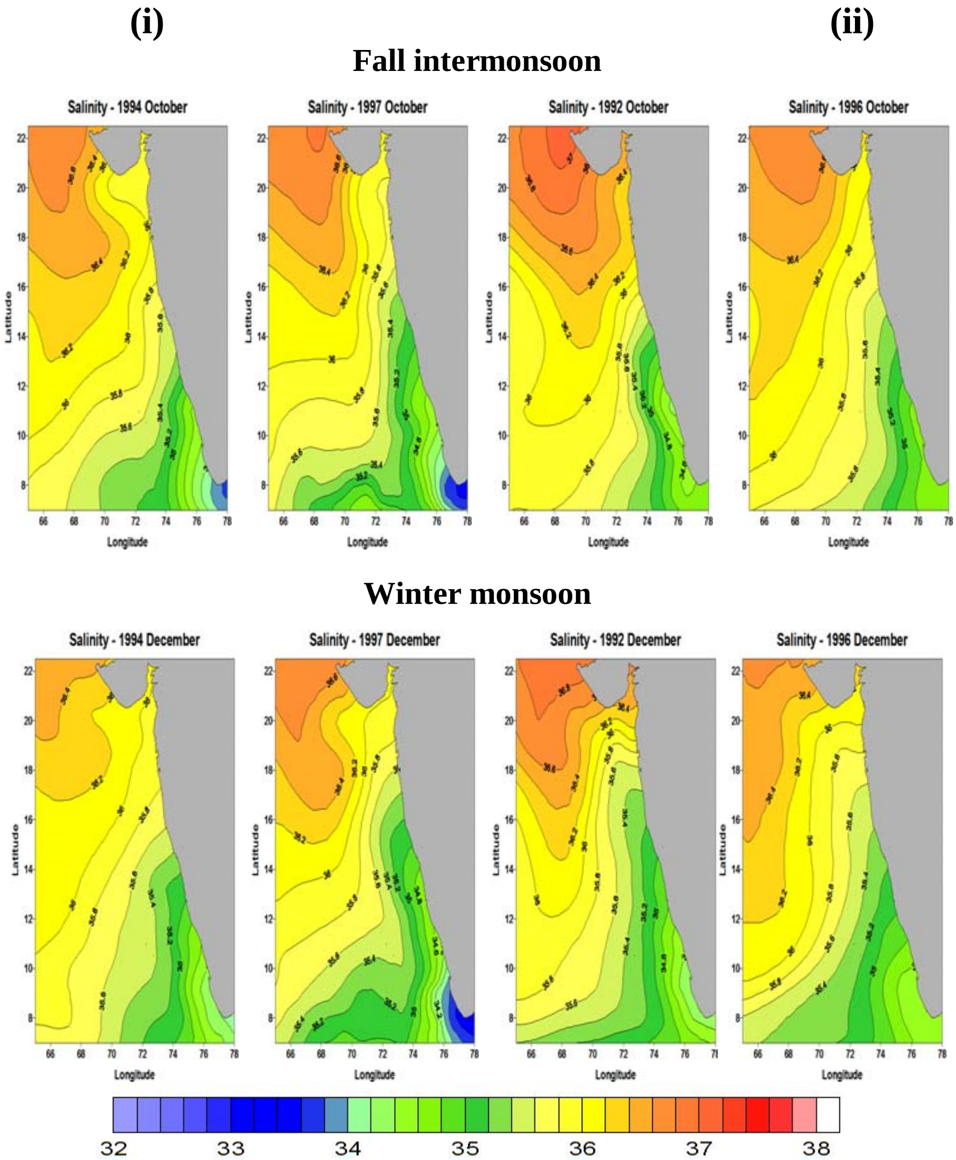


Fig. 3.12b: SSS of EAS in fall and winter monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

Figure 3.12a shows that during spring (April) the salinity distribution is almost in a similar pattern for both the positive and negative IOD years. The coastal waters of southwest coast of India are having a salinity range of 34.6-35.6 psu during this time. Whereas, during July the high saline tongue (35.6 psu) observed to be extending towards southeast up to 10°N. And the coastal SSS showed a decrease (~34.4 psu) during the month. The fall (October) and winter monsoon (December) seasons are characterized by strong SSS gradient (Fig. 3.12b) possibly due to the heavy summer monsoon rainfall during the positive IOD years of 1994 and 1997. Intrusion of low saline water during the season as reported by Vinayachandran *et al*., 2005 to the SEAS is observed maximum during the positive IOD years of 1994 and 1997. The SSS is lowering up to a minimum value of 33.4 psu during this time in positive IOD years.

Figure 3.13 shows the vertical distribution of salinity in SEAS for the month of September during 1994 and 1992. From the figure it is clear that the halocline became deeper (≈ 100m depth) in positive IOD year 1994 when compared to 1992, which was a negative IOD year. In 1992 the halocline depth was almost 80 m. The earlier reversal of winds from summer monsoon to winter monsoon during September 1994 explains the deviation of shallow halocline from normal pattern which substantiate the MLD variations as explained in the section 3.3.2.2.

The presence of Bay of Bengal low saline water (less than 34 psu) during the winter season of the positive IOD years suggests an increased measure of intrusion and is thus followed by anomalous warming of the upper column. Thus, it can be concluded that, the intensity of warm pool of the SEAS followed by a positive IOD is higher. This substantiates the earlier explanation regarding the hike in spring temperature during the year followed by a positive IOD year (Section 3.3.2.1).

Figures 3.14a and 3.14b show the distribution of SSS during winter in positive and negative IOD years respectively. In SEAS large negative anomaly can be seen during winter and it is mainly due to the intrusion of low saline water from Bay of Bengal through EICC. From the figures it is evident that in positive IOD years the negative anomaly is strong and the intrusion happens earlier than that during the negative IOD years. The reversal of the North Equatorial Current (NEC) also supports this intrusion of low saline water very strongly during positive IOD years. Masson *et al.* (2004) showed that during IOD years 1994 and 1997, large negative salinity anomalies were present to the north of the equator and large positive anomalies to the south.

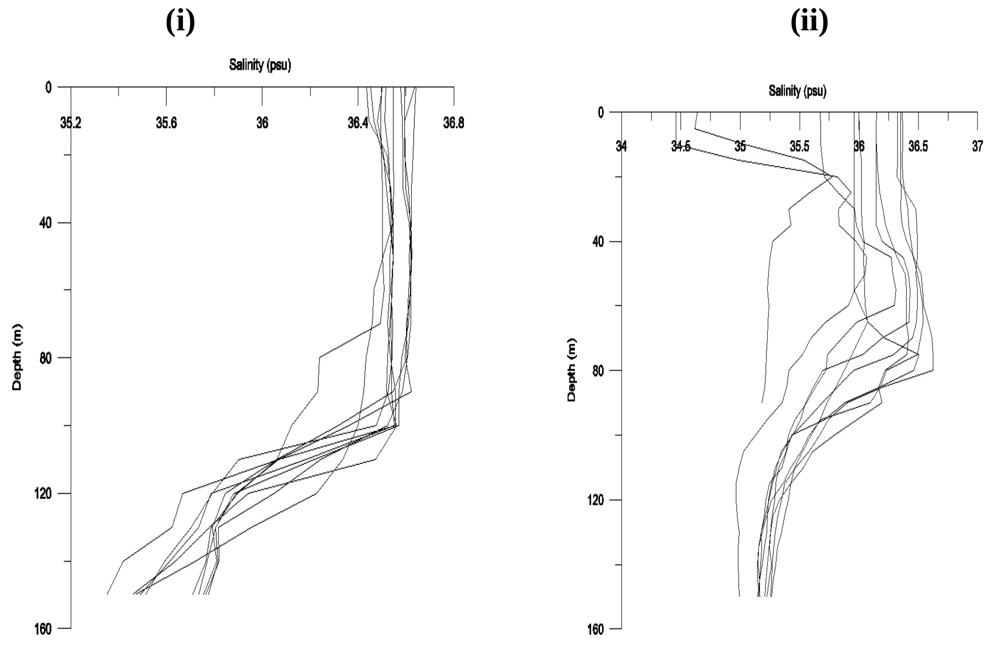


Fig. 3.13: Vertical distribution of salinity of EAS during September (i) 1994, he positive IOD year (ii) 1992, the negative IOD year

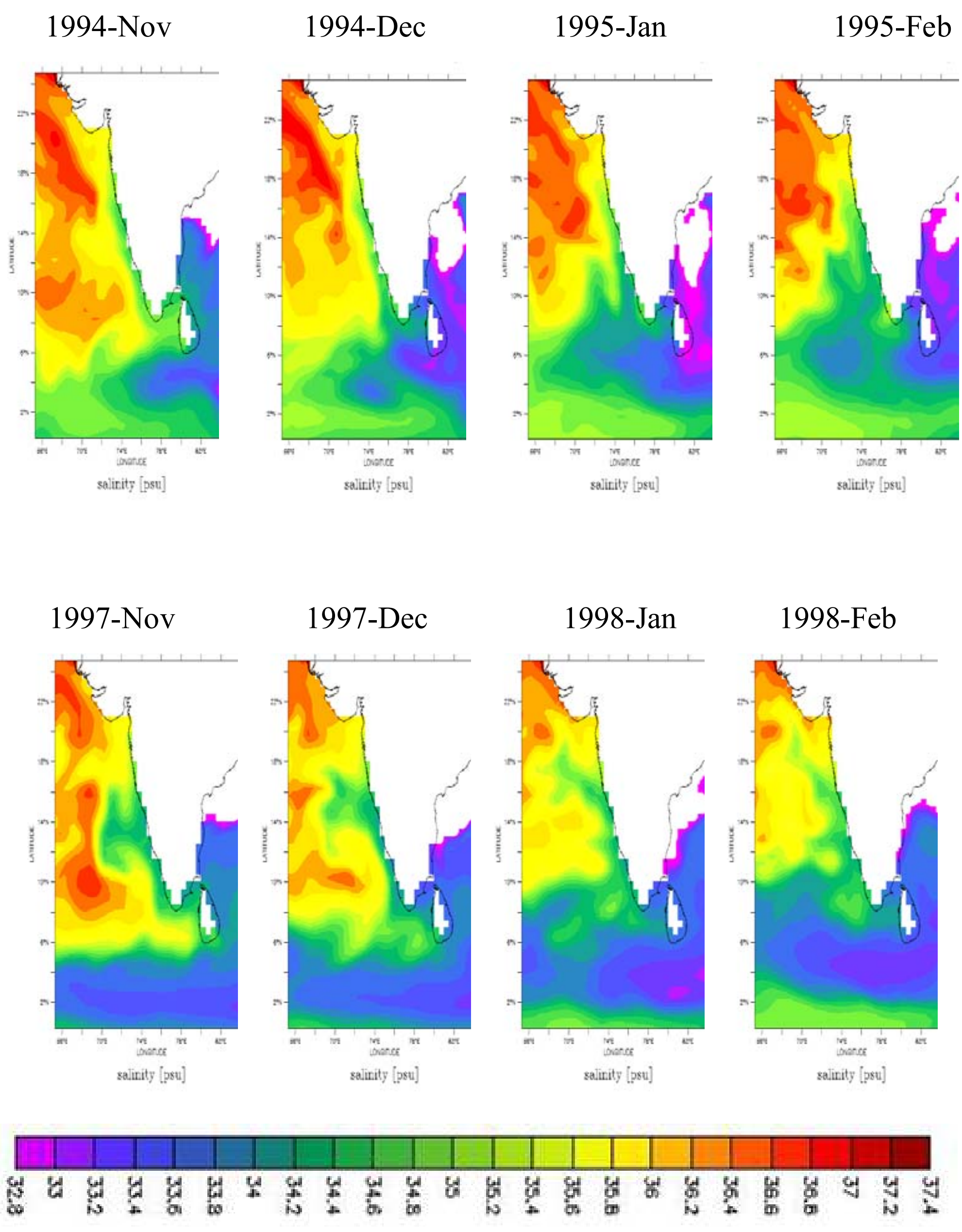


Fig. 3.14a: Distribution of salinity at 25m depth in winter monsoon during positive IOD years 1994-95 and 1997-98

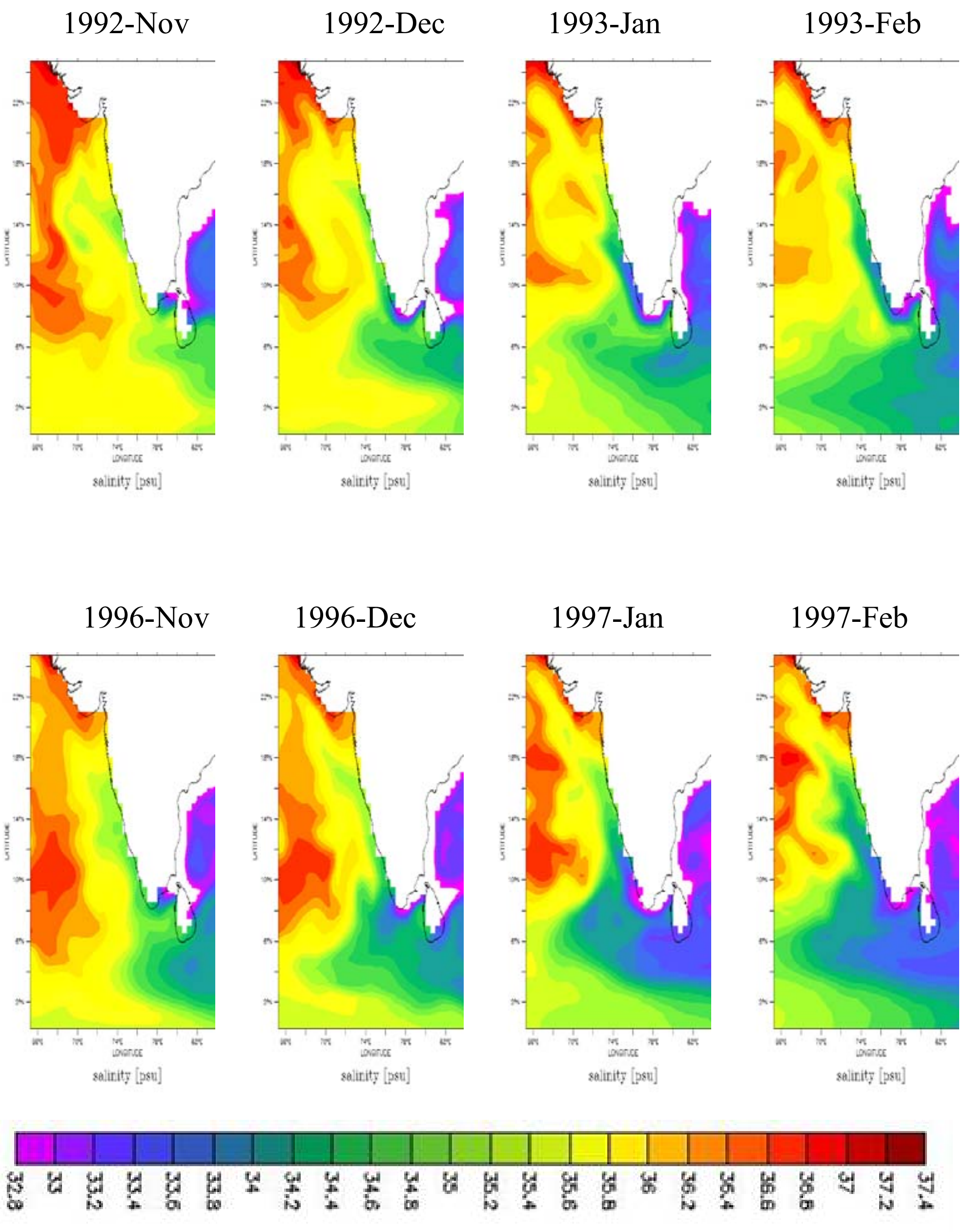


Fig. 3.14b: Distribution of salinity at 25m depth in winter monsoon during negative IOD years 1992-93 and 1996-97

3.3.2.4 Heat flux

Changes in heat stored in the upper layers of the sea surface can be described by the imbalance between the incident solar radiation flux, the long wave radiation flux emitted from the sea surface, the sensible heat and the latent heat fluxes from the sea surface to the atmosphere. The determination of the heat exchange through air-sea interface is very important for the investigation of thermal modifications in the lower atmosphere and the upper ocean. Air-sea temperature and humidity differences and cloud cover as well as wind speed contribute to the variability observed in these air-sea fluxes. Figure 3.15 shows the different components of surface heat flux in the EAS for the month October which is the peak phase of IOD. During the period the Short Wave Radiation (SWR) will be very high along the equator in normal years. From figure 3.15a, it is clear that the negative IOD years show a high SWR in the equatorial region. But during positive IOD years it is very less. In the eastern part of the study area SWR is very low (170-200 Wm^{-2}) during the positive IOD year 1994. Whereas, the pattern is different during 1997 which was a positive IOD year associated with the strongest El Niño. The negative IOD years 1992 and 1996 showed values between 190-230 Wm^{-2}. The cloud feedbacks collectively determine the surface SWR budget (Curry *et al*., 1996; Vavrus, 2004).

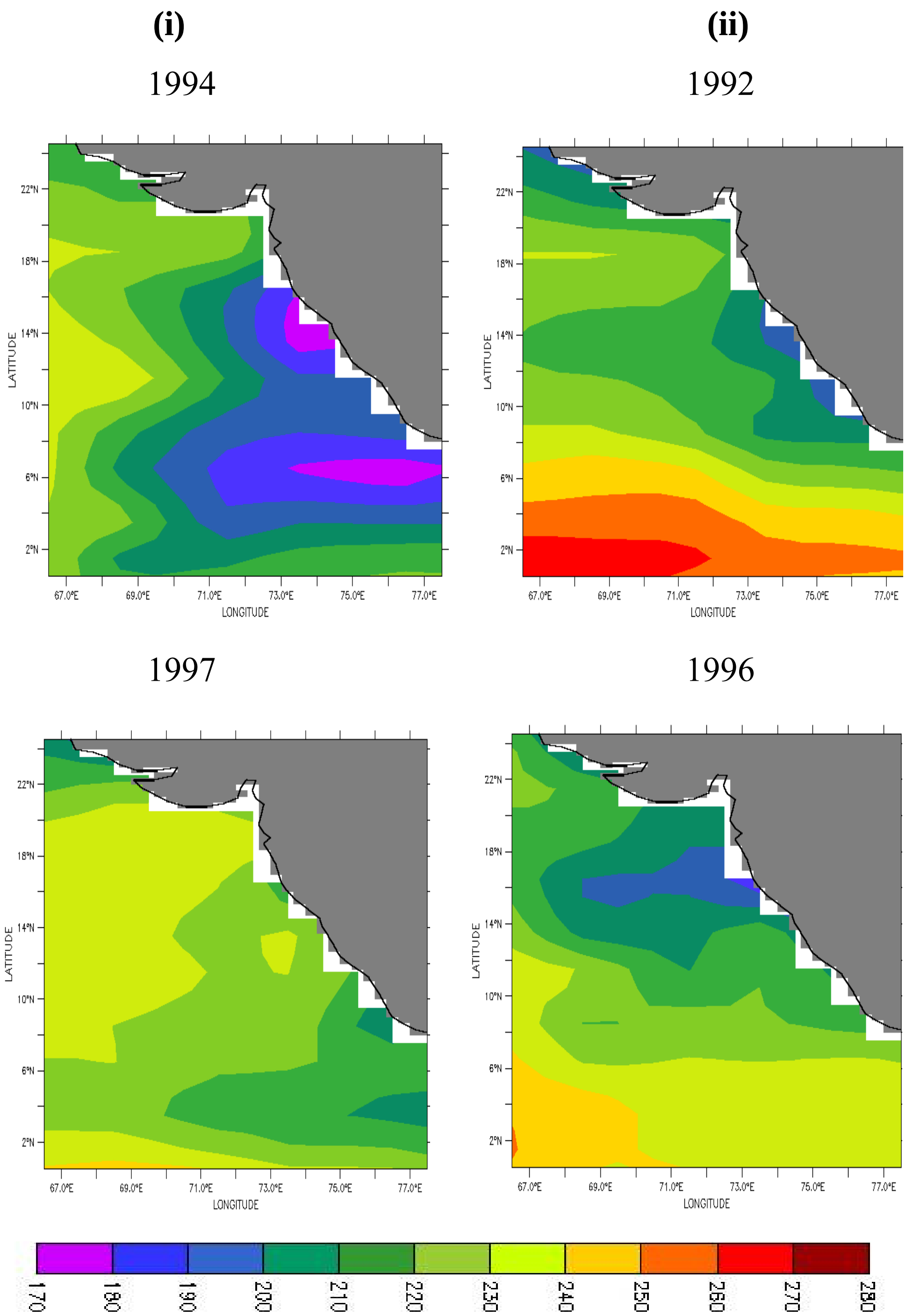


Fig. 3.15a: Short Wave Radiation over EAS in October during (i)Positive IOD years (ii) Negative IOD years

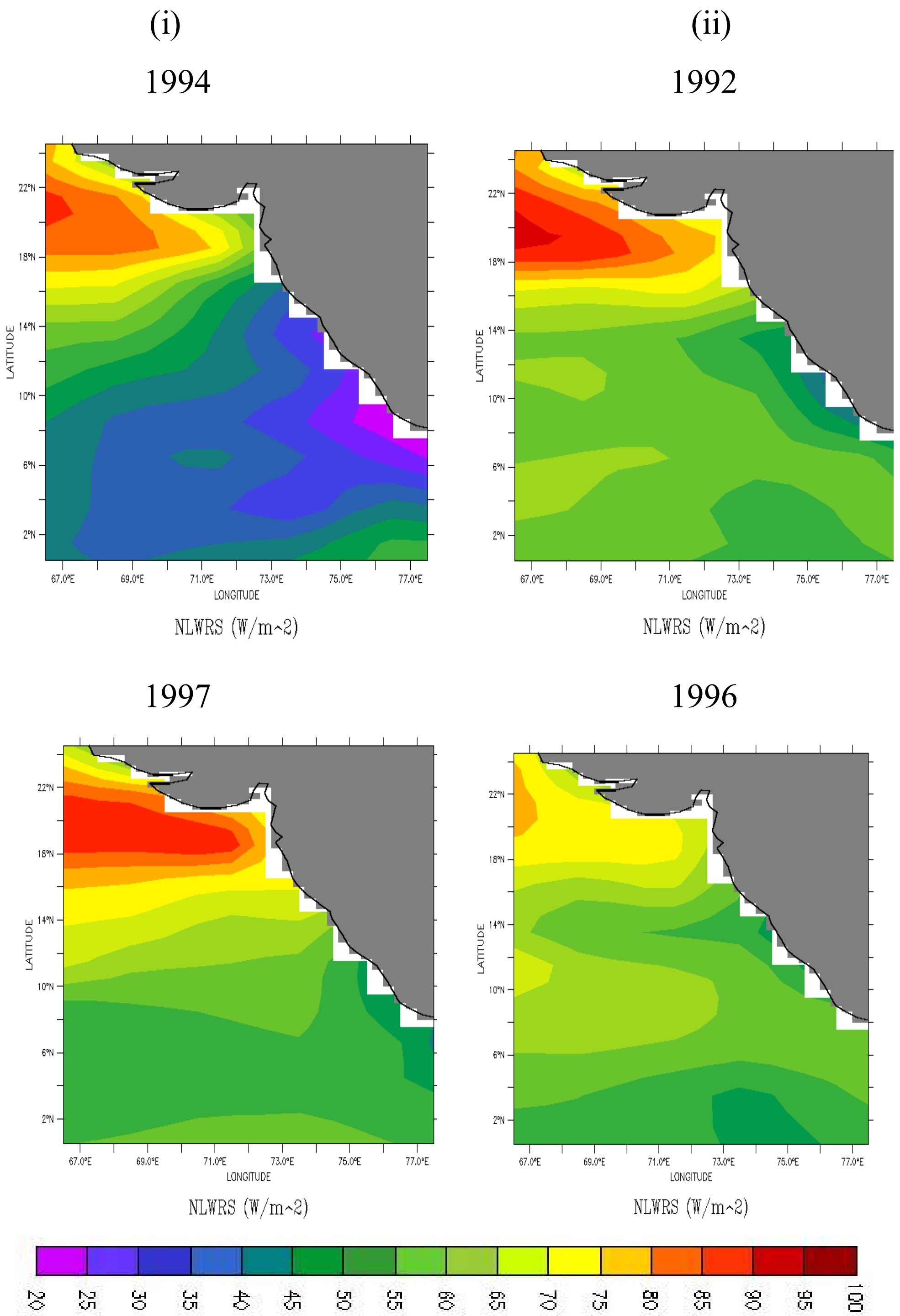


Fig. 3.15b: Long Wave Radiation over EAS in October during (i) Positive IOD years (ii) Negative IOD years

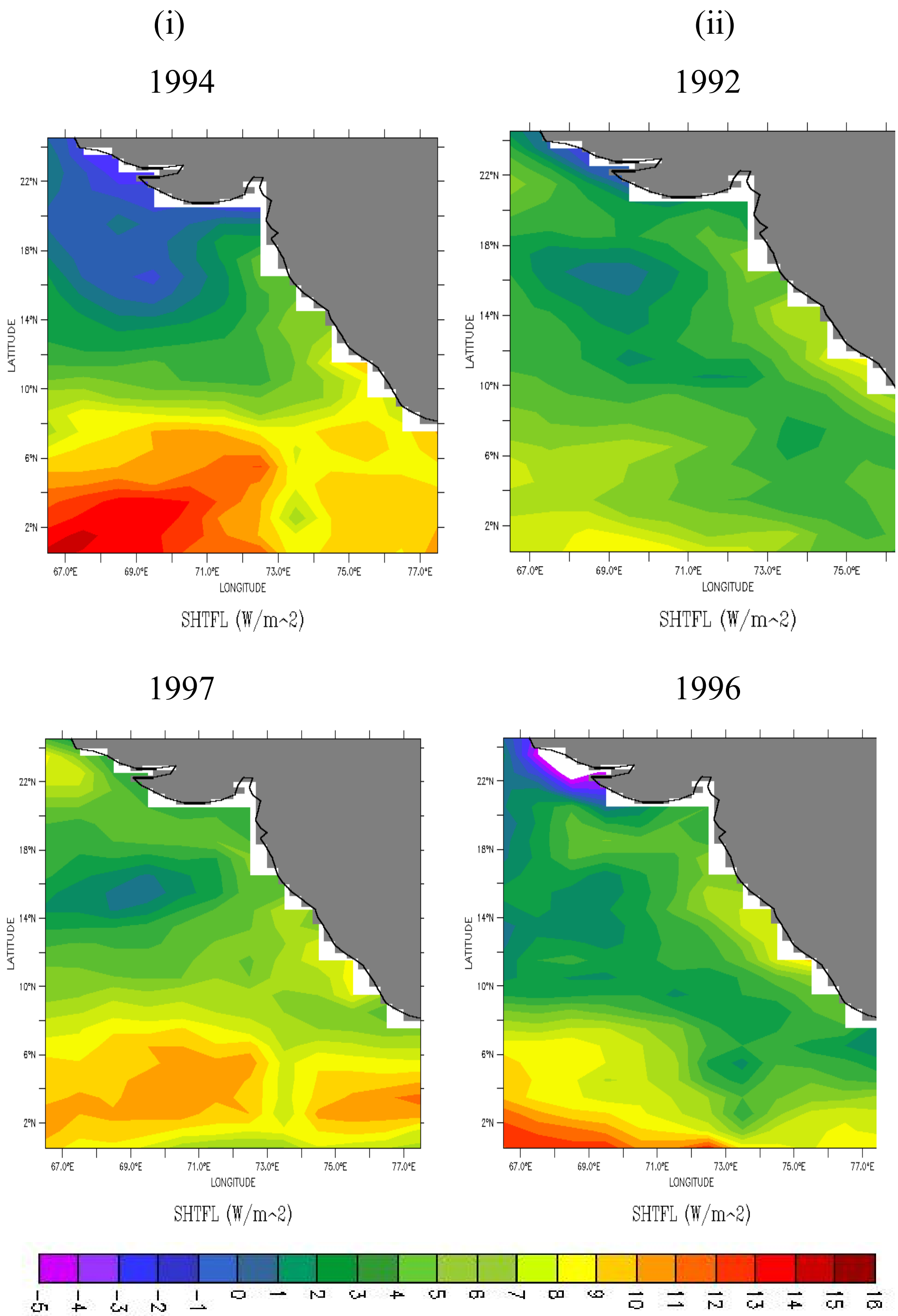


Fig. 3.15c: Sensible Heat Flux over EAS in October during (i) Positive IOD years (ii) Negative IOD years

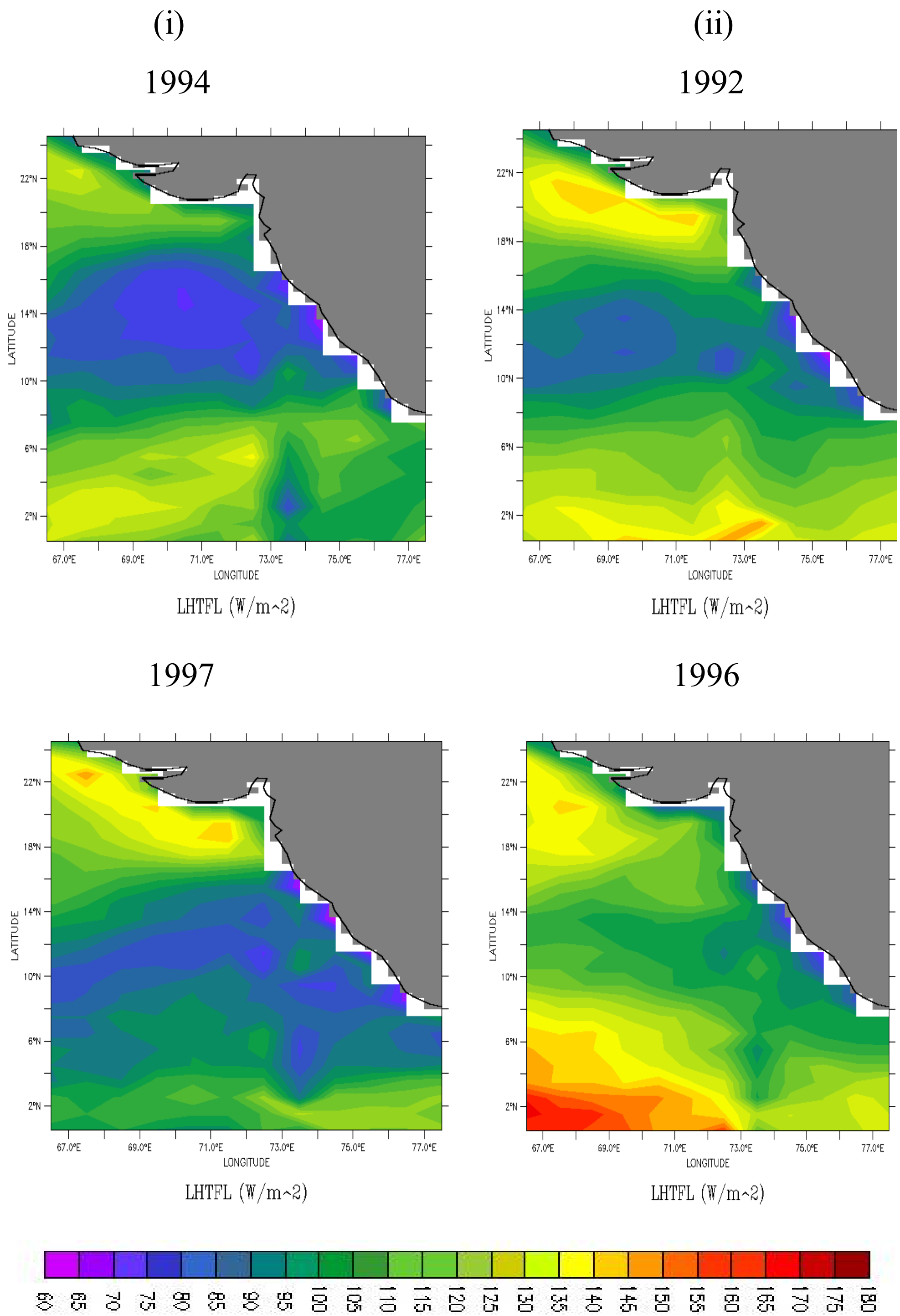


Fig. 3.15d: Latent Heat Flux over EAS in October during
(i) Positive IOD years (ii) Negative IOD years

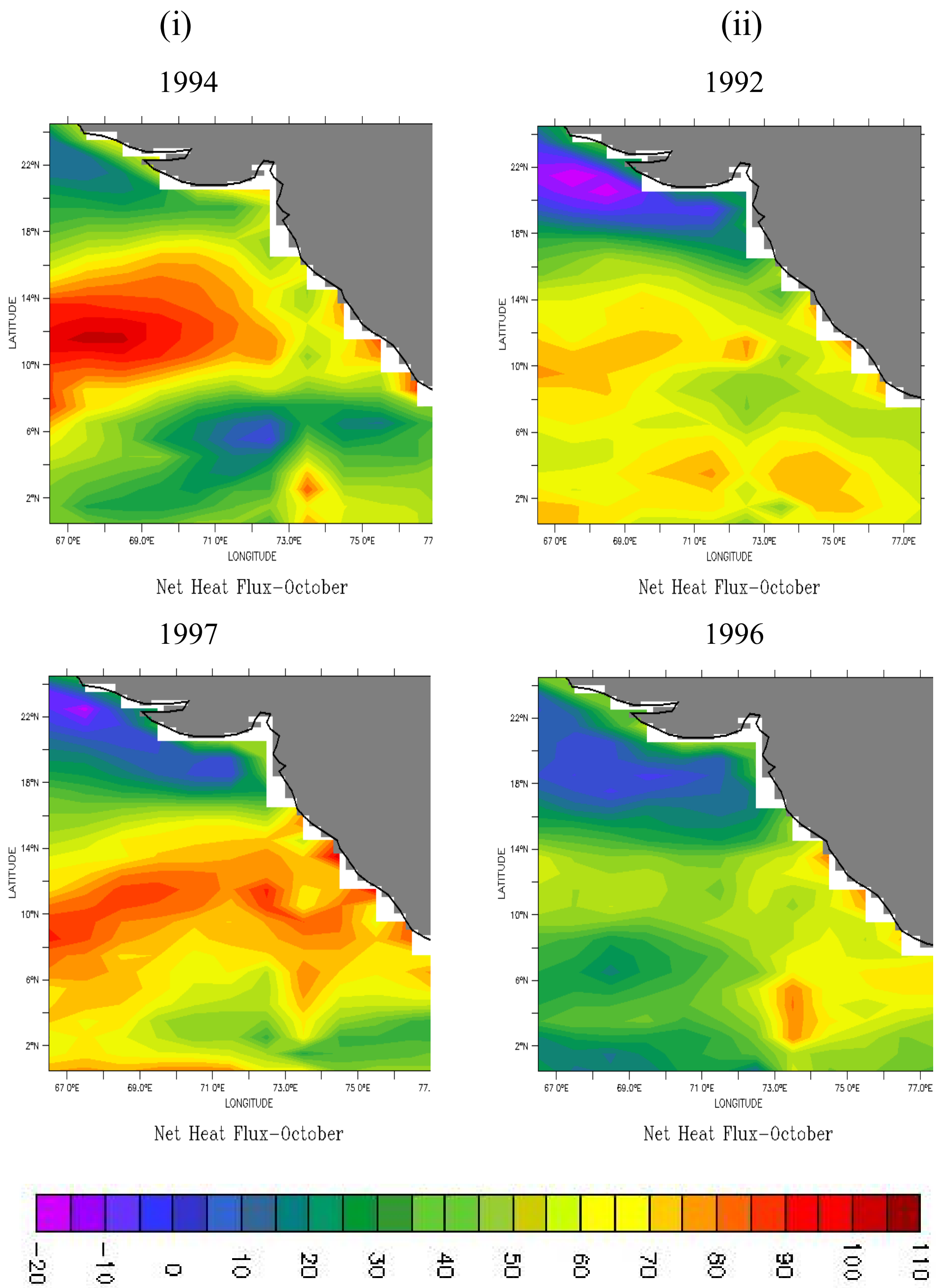


Fig. 3.15e: Net Heat Flux over EAS in October during
(i) Positive IOD years (ii) Negative IOD years

SWR in the Arabian Sea is highly influenced by the seasonal variations and the extensive cloud cover during summer monsoon reduces the SWR considerably (Fig. 3.15a). This may extend to fall inter monsoon also. In the present analysis it is observed that, during positive IOD years the SWR is very low during the fall and the subsequent winter monsoon seasons.

The cloud cover reduces the net long wave radiation (LWR) also (Sultan and Elghribi, 2002). The analysis during the four years shows a similar pattern in LWR in the range 40-90 Wm^{-2} with considerable north south variation. The values were very high at north (75-95 Wm^{-2}) compared to the southern side (40-60 Wm^{-2}). The case was exceptional during 1994, the positive IOD year where the southern region showed very low value of LWR in the range 20 – 45 Wm^{-2} (Fig. 3.15b).

When the ocean surface is warmer than the air above, heat will be transferred upwards into the air as a positive sensible heat Flux (SHF) and when evaporation is taking place there is a positive latent heat flux (LHF). Figure 3.15c shows the SHF during positive and negative IOD years. In SEAS, during positive IOD years 1994 and 1997 the relative change in SHF is significant (8 to 14 Wm^{-2}). But during negative IOD years it comes only below 8 Wm^{-2}. At the northern part of the area the SHF is negative and was significant during 1994. The exchange of LHF from the ocean to atmosphere is very low during positive IOD years i.e., evaporation is low (Fig. 3.15d). The figure shows that in the central as well as southern part of the EAS the latent heat loss is between 70 – 100 Wm^{-2} during positive IOD years. During negative IOD years latent heat loss is more when compared to positive IOD years.

The net heat flux (NHF) exchange at the air-sea interface is a key dynamic feature in determining the heat content of the ocean basin (Weller *et al.*, 1998). The NHF over EAS shows a heat gain during October (Fig. 3.15e) which indicates the SST is less than the equilibrium temperature. The equilibrium temperature is a hypothetical water surface temperature i.e., when the SST at equilibrium temperature, the NHF exchange between the sea surface water and the air would be theoretically zero (Abualnaja, 2009). During positive IOD years the heat gain is high (70-100 Wm^{-2}) between 8°N–16°N when compared to negative IOD years. Even if there is a decrease in short wave radiation, the NHF is high during positive IOD years. This may be due to the advection of water mass with high heat gain towards EAS through currents.

3.3.2.5 Sea Surface Height and depth of 20°C isotherm

SSHA is the most profound parameter to explain the phenomenon like upwelling and downwelling. Along the west coast of India upwelling has been observed during summer monsoon and downwelling in winter monsoon.

The present analysis shows variations in SSH between the positive and negative phases of IOD (Fig. 3.16a & b). Summer monsoon during negative IOD years are recorded with a decreased SSH than that during positive IOD years. During the negative IOD years there are significant changes in winter season in terms of coastally trapped wave propagation, when compared to the positive IOD years. During 1996 and 1998 in the month of October SSH all over the Arabian Sea is lower as compared to the positive IOD years (3.16b). But in December there was a rapid hike in SSHA along the coastal region during negative IOD years. This is a clear indication of the presence of coastally trapped downwelling Kelvin waves supporting Rao *et al*. (2009).

Similar pattern is also observed in the case of D20 (depth of 20°C), which is assumed as the centre of the thermocline (Fig 3.17a&b). D20 is the indicator of the path of the Kelvin wave (Yu, 2003) and it also reflects the variability of MLD (sub surface variability). As compared to the positive IOD years, the negative IOD years showed an uplift of D20 along the west coast of India especially during summer monsoon and fall. This indicates the upsloping of the upwelling mode Kelvin wave. But in December these isotherms deepened and confined to the coast in negative IOD years. During positive IOD years there is no considerable variability in D20.

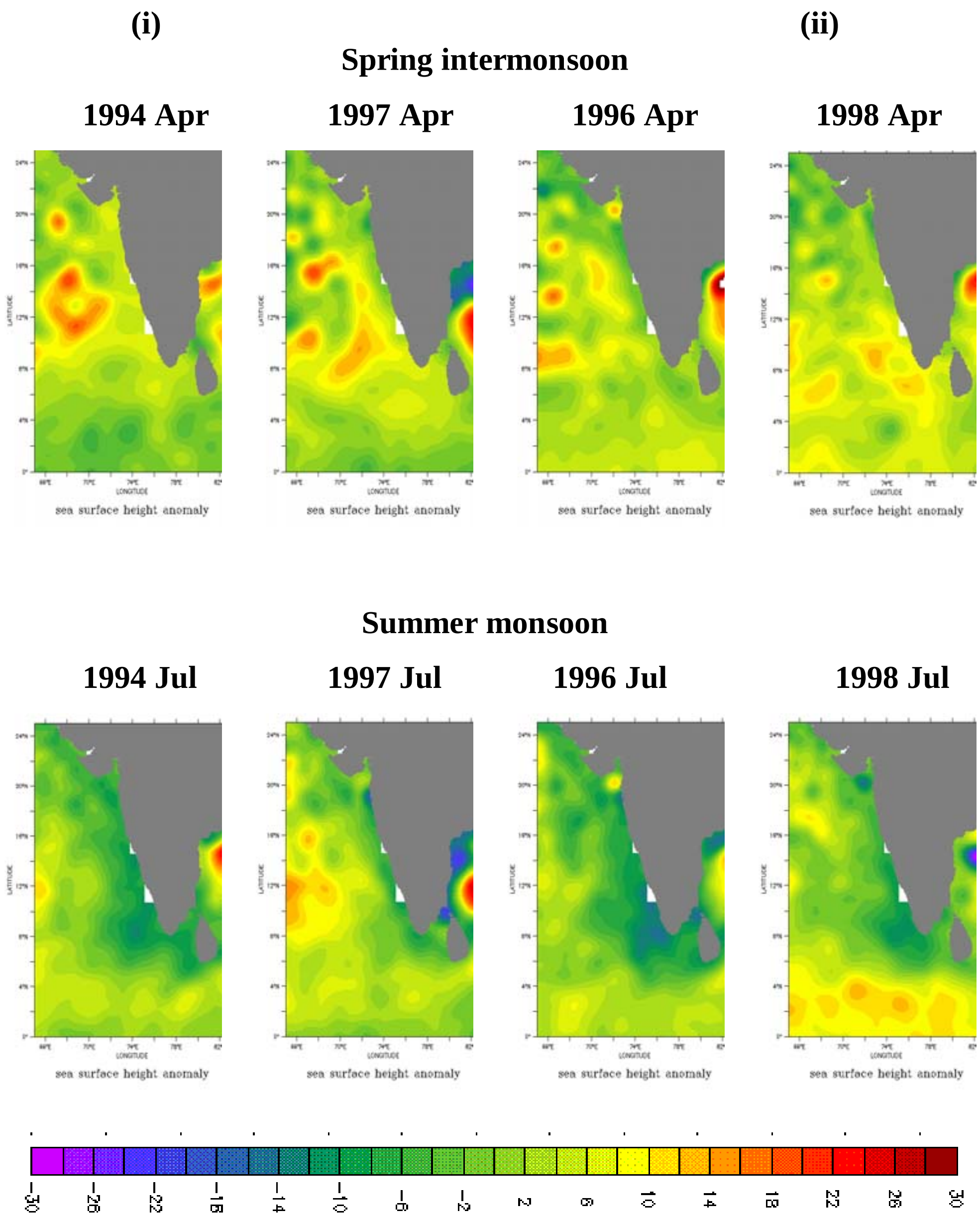


Fig. 3.16a: SSHA during spring and summer monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

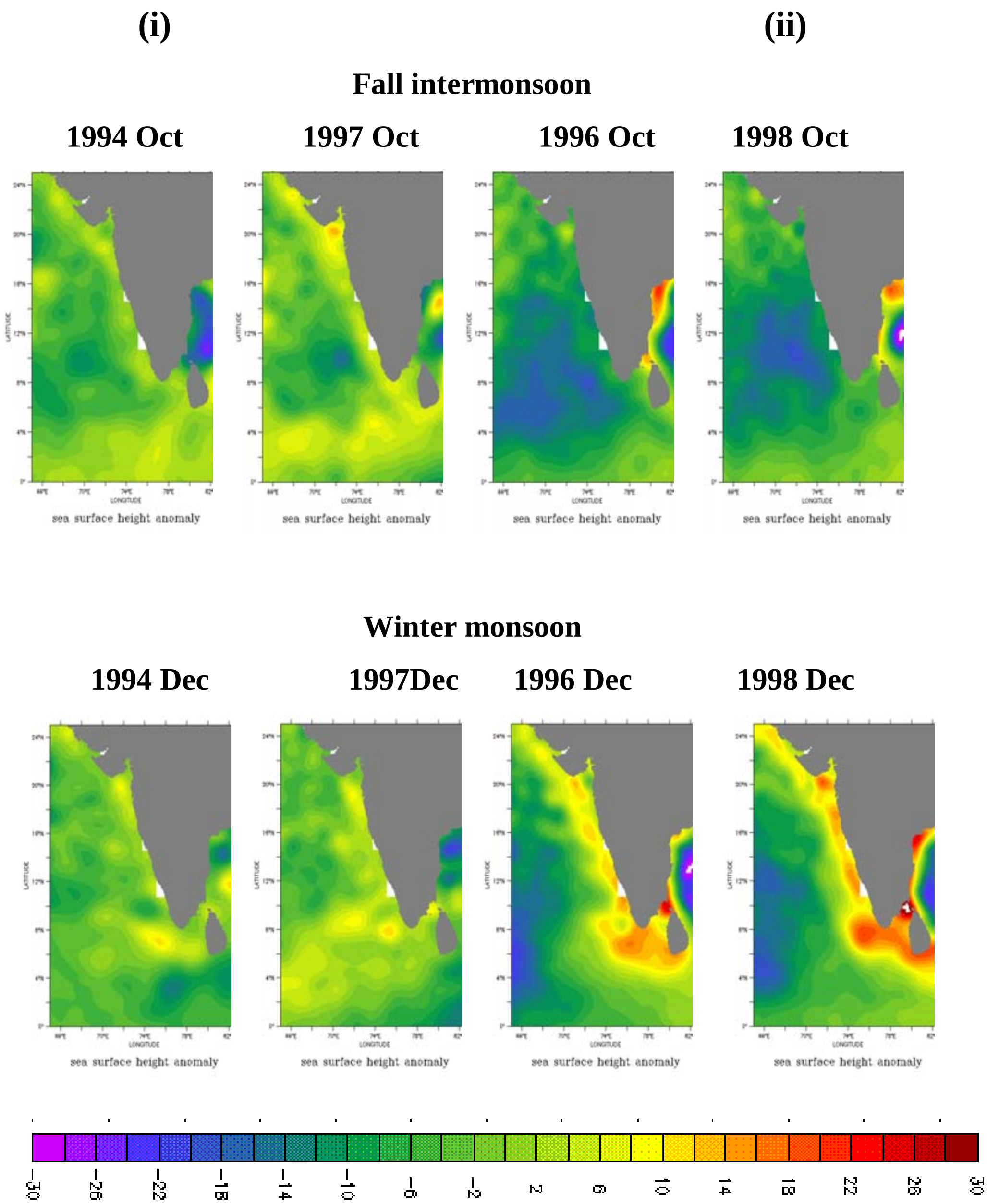


Fig. 3.16b: SSHA during fall and winter monsoon seasons during (i) Positive IOD years (ii) Negative IOD years

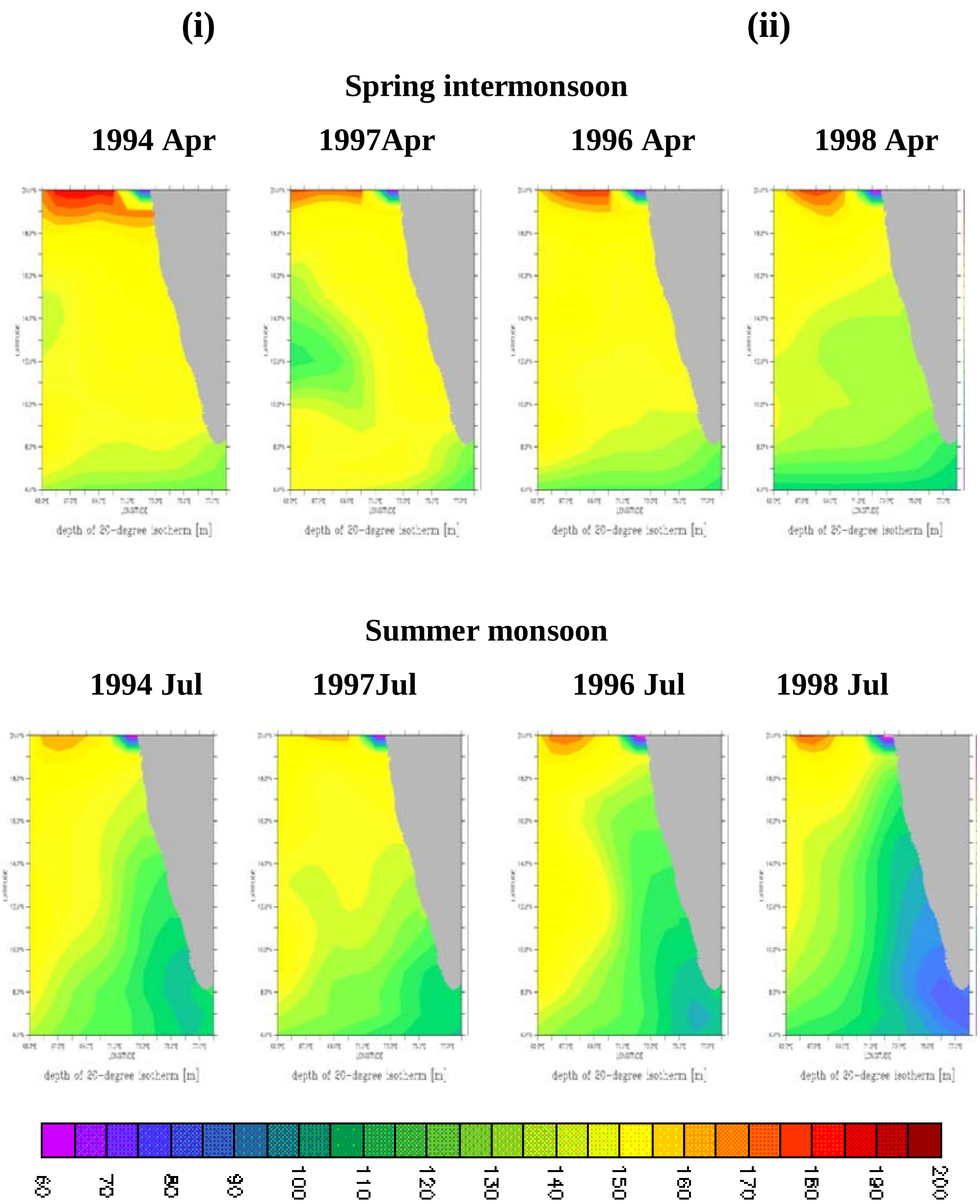


Fig. 3.17a: Distribution of depth of 20°C isotherm (D20) in spring intermonsoon and summer monsoon during (i) Positive IOD years (ii) Negative IOD years

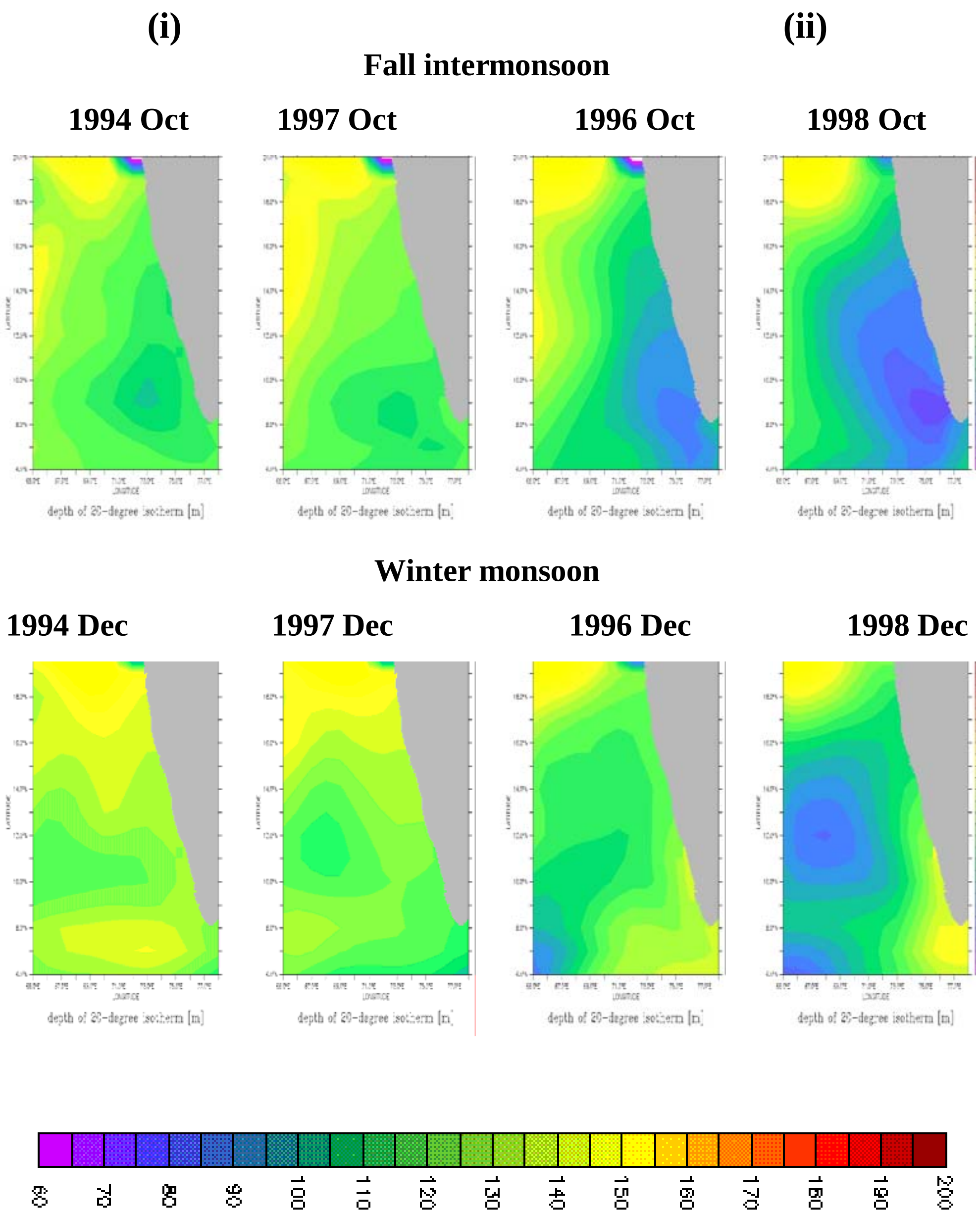


Fig. 3.17b: Distribution of depth of 20°C isotherm (D20) in fall intermonsoon and winter monsoon seasons during (i)Positive IOD years (ii) Negative IOD years

3.3.2.6 Currents

Figure 3.18 represents the zonal surface current variability of EAS (averaged over the latitudes 0 – 7°N) during positive and negative IOD years. In these years the currents are towards west (-ve) during winter monsoon (Nov-Feb). In both positive IOD years (1994 and 1997) and negative IOD years (1996 and 1998) during spring time (Mar-May) the current starts to flow towards east (+ve). During negative IOD years the current reverses in April itself, but during positive IOD years it happens only in May. In the case of equatorial current, in positive IOD years the currents during summer monsoon is towards west (Brown *et al*., 2008). But in EAS (0 – 7°N) the current is towards east with very less intensity. In negative IOD years these currents are very strong towards east.

Figure 3.19a&b shows the geostrophic current pattern of EAS associated with SSH during positive and negative IOD years. From the figure 3.19a it can be concluded that for spring season the geostrophic current pattern is almost similar for positive and negative IOD years. During summer monsoon, the currents are towards south along west coast of India. Figure 3.19b shows the geostrophic current pattern of EAS during fall and winter season. During October, the coastal waters of west coast of India showed a current pattern towards north in positive IOD years and towards south in negative IOD years. SSH also showed a major decrease during negative IOD years when compared to that in positive IOD years. In winter, during negative IOD years there was a strong geostrophic current flowing towards north which was very much confined to the coast. This phenomenon is not identified during positive IOD years.

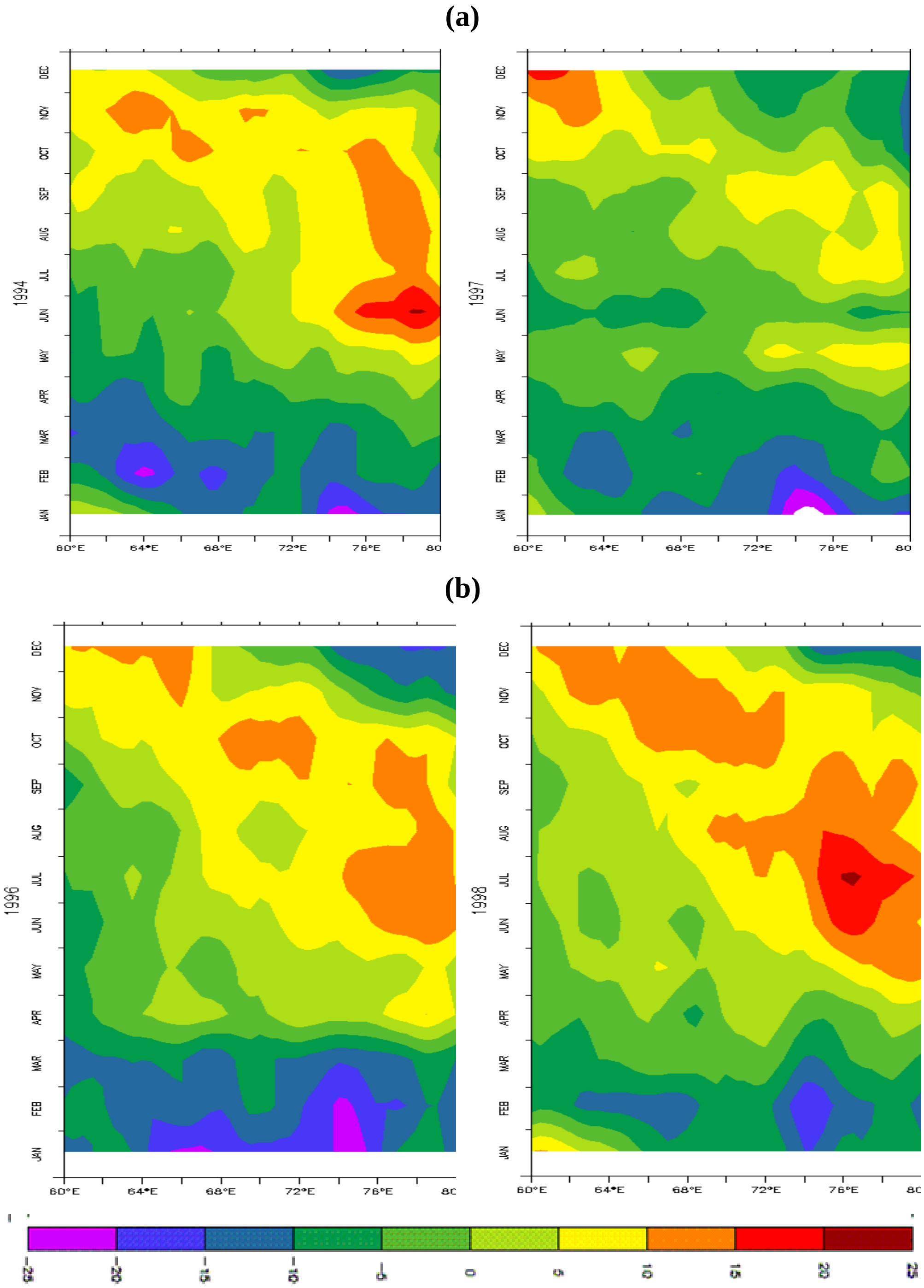


Fig. 3.18: Zonal surface current distribution of EAS (averaged 0-7°N) during (a) Positive IOD years 1994 and 1997 (b) Negative IOD years 1996 and 1998

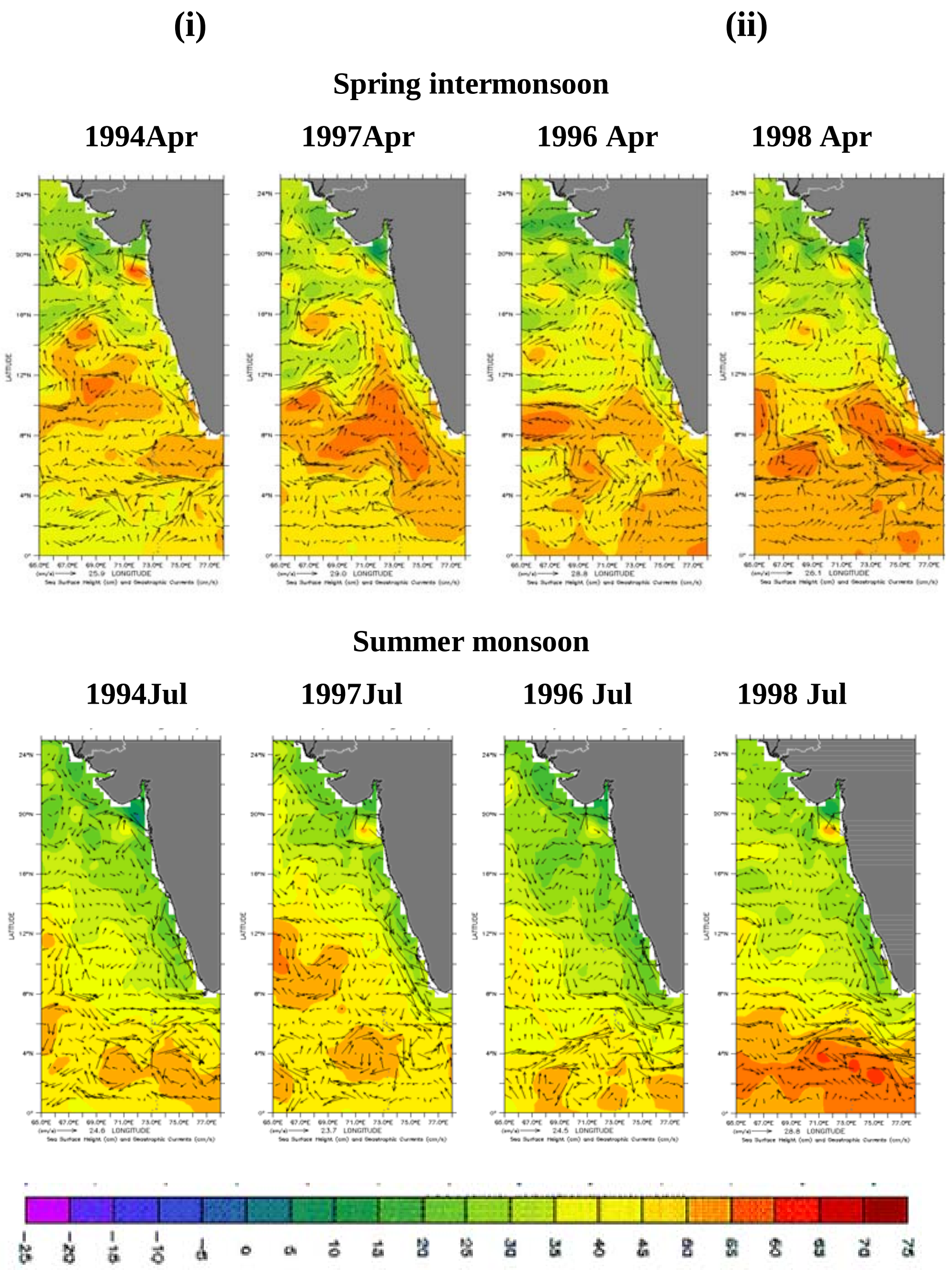


Fig. 3.19a: Geostrophic currents of EAS in spring intermonsoon and summer monsoon seasons during (i)Positive IOD years (ii) Negative IOD years

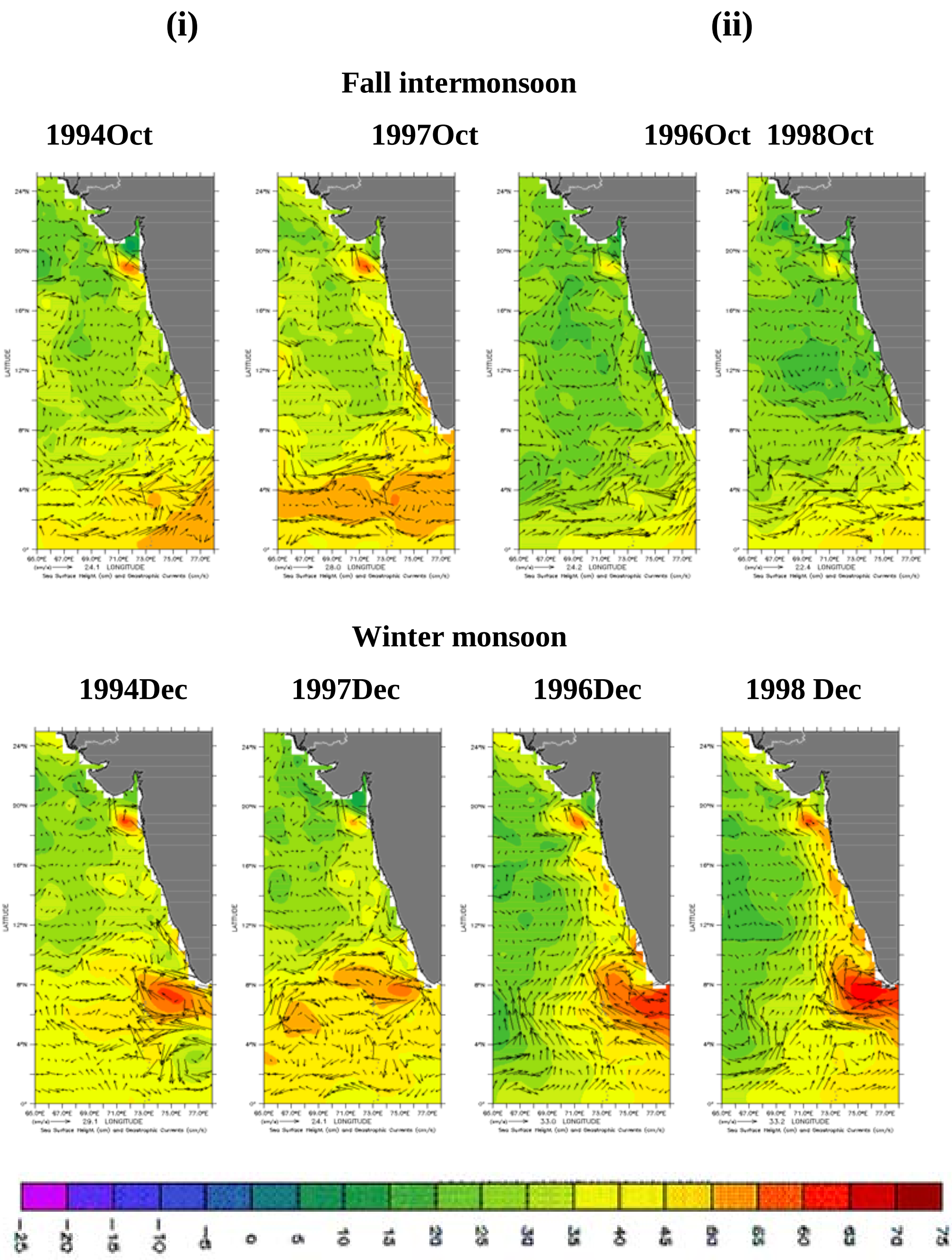


Fig. 3.19b: Geostrophic currents of EAS in fall intermonsoon and winter monsoon seasons during (i)Positive IOD years (ii) Negative IOD years

3.3.2.7 Coastal upwelling and primary production

With the onset of southwest monsoon, the upwelling starts to occur along southwest coast of India. It starts from southern most coast near Kanyakumari and then spreads northwards along the coast with the advancement in monsoon (Smitha *et al.*, 2008). Coastal upwelling is caused by wind induced divergence due to Ekman transport (Sverdrup *et al.*, 1942). During southwest monsoon a clockwise circulation develops in the Arabian Sea that leads to an equatorward coastal current West India Coastal Current (WICC) (Shetye *et al.*, 1990). Coastal upwelling of southwest coast of India has reflective impacts on the coastal fisheries. The west coast of India accounts for 70% fish yield of the total Arabian Sea production (Luis and Kawamura, 2004) in which 53% is from the southwest coast alone (Sanjeevan *et al.* 2009). As direct measurement of the intensity or the quantification of upwelling is intricate, it can be approximated by knowing the chlorophyll *a* concentration. Another way to quantify upwelling is the usage of upwelling index. LTA and strength of Ekman transport has been considered as good upwelling indices and the interannual variability thereof is examined here.

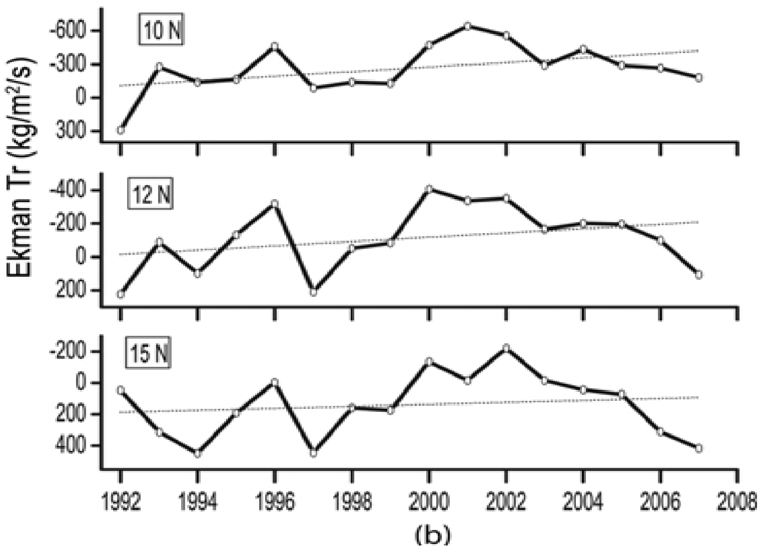


Fig. 3.20: Temporal variability of the offshore Ekman mass transport at 10°N, 12°N, 15 °N latitudes during Summer monsoon (after: Jayaram *et al.*, 2010)

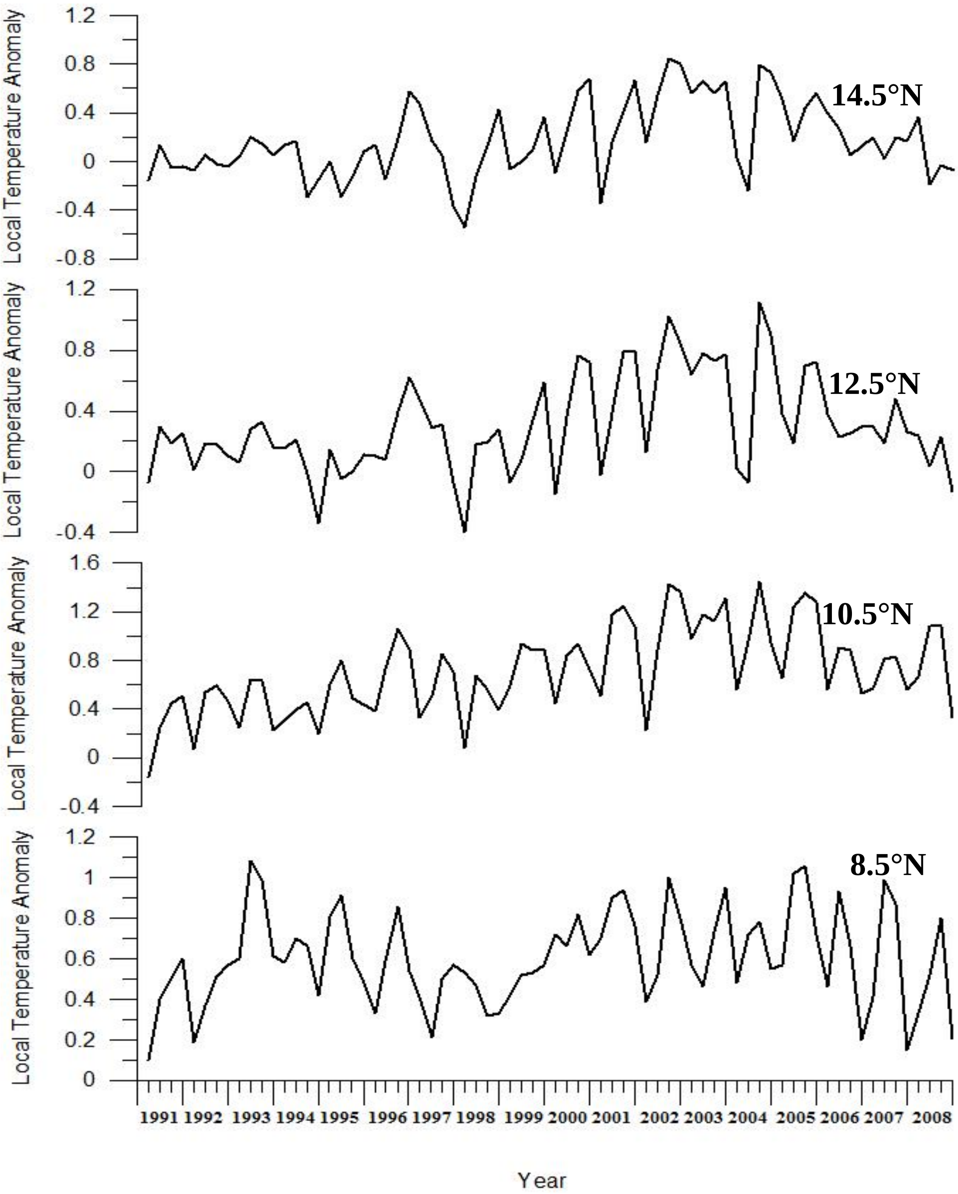


Fig. 3.21: Interannual variability of upwelling index (LTA) at four regions of southwest coast of India (8.5°N, 10.5°N, 12.5°N, 14.5 °N latitudes) during Summer monsoon

The strength of upwelling can be estimated based on the wind speed and the Ekman transport (Bakun, 1973). The meridional winds are considered for the estimation of Ekman transport. Interannual variability of offshore Ekman mass transport at 10°N, 12°N and 15°N along southwest coast of India during 1992-2007 is shown in Figure 3.20 (Jayaram *et al.*, 2010). In 1994 and 1997 (positive IOD years) the Ekman transport was very low. High Ekman offshore transport was observed during 1996 (negative IOD year) and also during 2000-2004 in summer monsoon. Later from 2005 to 2007, offshore Ekman transports have decreased.

Another index for the upwelling intensity is LTA which can be derived from SST. As upwelling regions are characterized by relatively cooler waters than the surrounding areas, a difference in the temperature of that region with a region far away from the coast along the same latitude, can be considered as a measure of upwelling intensity (Wooster *et al.*, 1976; Naidu *et al.*, 1999; Smitha *et al.*, 2008). Figure 3.21 shows the upwelling index of southwest coast of India in terms of LTA. From the figure it is clear that in the positive IOD years 1994 and 1997, upwelling intensity was less. In 1996 there was an increase in LTA, which represents the negative IOD year. During 1991-1998, the upwelling intensity was less and after that it increased. Again after 2005, it showed a decreasing trend.

The immediate biological response of this physical process in the area can be observed in the surface chlorophyll *a* distribution (Figure 3.22) which represents the primary production of the region. Along the SEAS, the most productive season is the summer monsoon and this is highly related to the intensity and spatio-temporal variation of coastal upwelling during June-September.

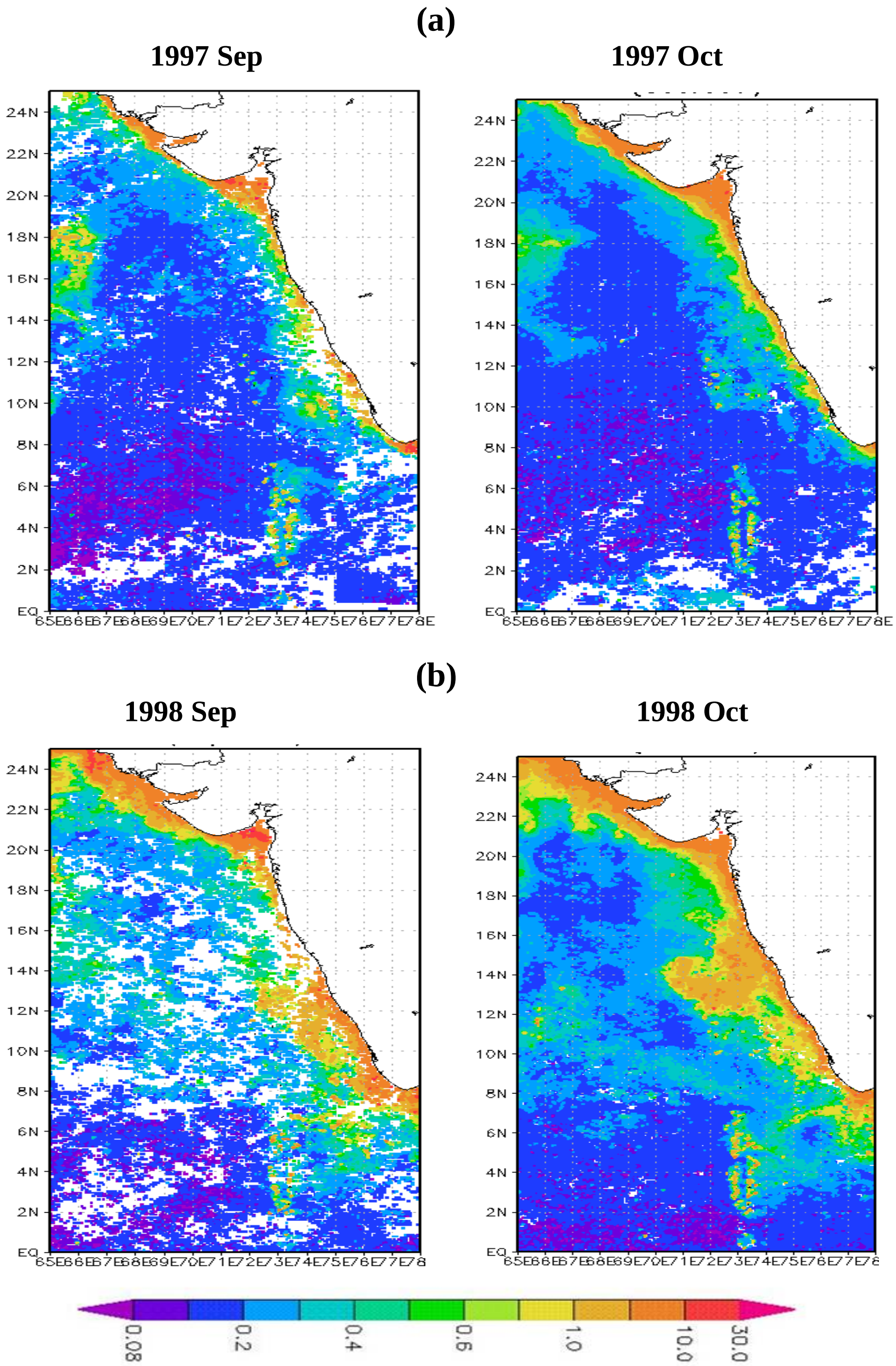


Fig. 3.22: Distribution of Chlorophyll a concentration during (a) Positive IOD year 1997 (b) Negative IOD year 1998

The higher level production including the fishery of the region is strongly influenced by this process. Also this is assumed to be influenced by the climatic events like the occurrence of IOD and to explore this; the surface Chlorophyll *a* pattern during the two IOD years has been analyzed. Because of the unavailability of satellite data before 1997 September, the positive IOD year 1994 and negative IOD years 1992 and 1996 could not be included in this study. Also the analysis was restricted for two months, September and October as the satellite data (Ocean color) were not available for the strong monsoon months of June-August due to extensive cloud coverage. During 1997-1998, which was a strong positive IOD year associated with strong El Niño, the chlorophyll *a* concentration of EAS is found to be less. But during 1998-1999 which was a negative IOD year with strong La Niña the chlorophyll *a* concentration was very high. This result also supports the upwelling characteristics of south west coast of India during IOD years.

3.3.2.8 Rainfall

Figure 3.23 shows the interannual variability of Summer Monsoon Rainfall (SMR) of the coastal states (Kerala and Karnataka) of southwest coast of India during the period 1991-2006. For both these states the summer monsoon rainfall showed a decreasing trend.

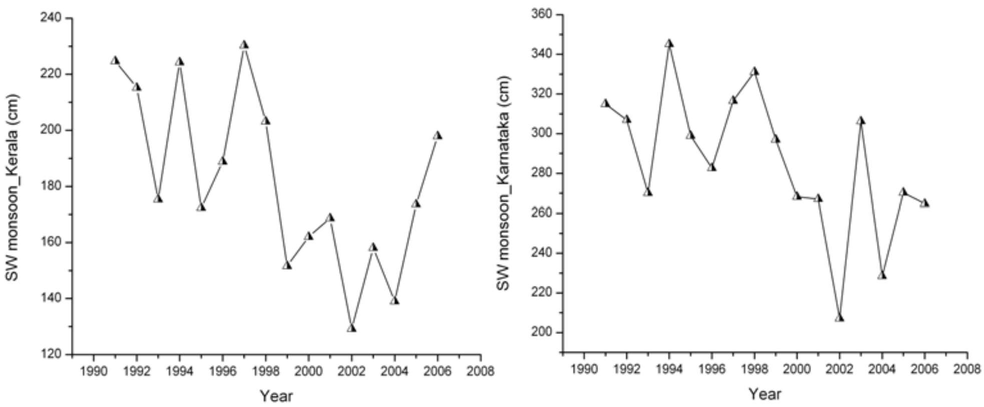


Fig. 3.23 Interannual variability of Summer Monsoon rainfall for Kerala and coastal Karnataka

One of the most important global phenomena which have a teleconnection with ISM is the ENSO (Sikka, 1980; Webster *et al.*, 1998). The warmer phase of ENSO, the El Niño weakens the ISMR to a large extent whereas, the colder phase of ENSO, the La Nina is associated with excess rainfall. However, study by Kumar *et al.* (1999) suggests that the effect of ENSO on ISMR has apparently weakened in the last two decades of the 20th century. The weakening of the ENSO–ISMR relationship is suggested as because of the frequent occurrence of strong positive IOD events that neutralize the impact of the ENSO. This is because the ISMR is positively correlated with DMI, whereas it is negatively correlated with the ENSO index (Ashok *et al.*, 2001).

During the period 1991-2008, there were a number of El Niño events associated with IOD upto 1998. But as expected, the SMR was not weak or deficit during the warm phase of the ENSO but was above normal for almost all the years. And this is suggested as due to the frequent occurrence of IOD events in the Indian Ocean. But after 1998, the SMR during the El Niño years were below the normal. The normal value of summer monsoon rainfall for Kerala is 186 cm and for Karnataka it is 292 cm, which is calculated from the long term rainfall data (1951 to 2006). 1994 and 1997 were two major positive IOD events of the decade and in those years the rainfall was heavy. Though there were frequent El Niño events during 1991-1998 the rainfall rate was very high for Kerala and Karnataka due to the frequent occurrence of positive IOD events.

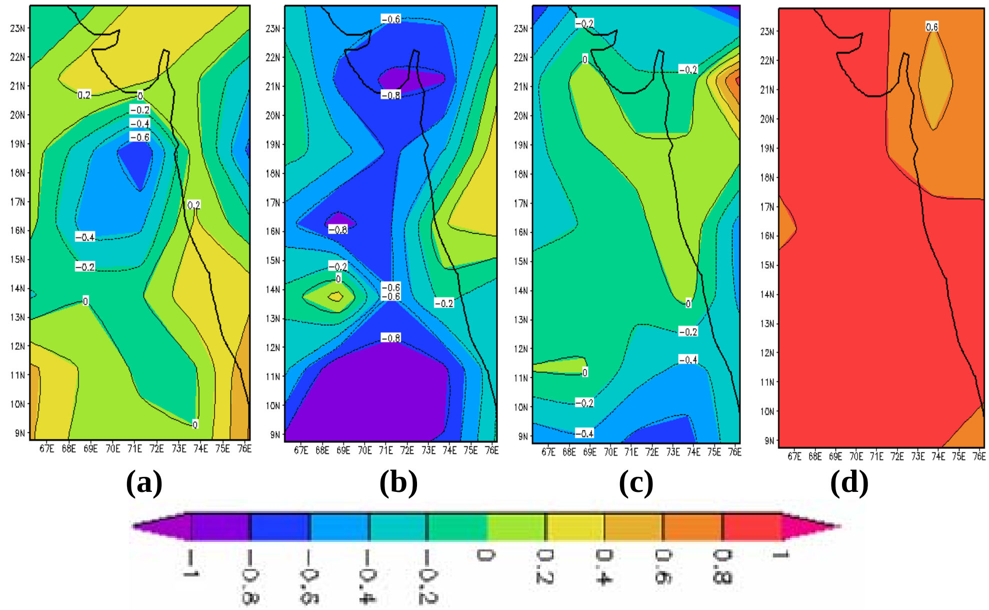


Fig. 3.24: Spatial distribution of partial correlations between Summer Monsoon rainfall and (i) positive Nino 3.4 index during 1991-1999 (ii) positive Nino 3.4 index during 2000-2008 (iii) negative Nino 3.4 index during 1991-1999 (iv) negative Nino 3.4 index during 2000-2008

To examine the influence of IOD on the SMR and its relationship with ENSO, the spatial distribution of partial correlations between these has been done. Figure 3.24 represents these spatial correlations between Nino 3.4 index (ENSO index) and SMR. From the figure 3.24 (a & b), it can be seen that during 1991-1999 when the IOD events were frequent, the El Niño - monsoon relationship was weak. But for 2000-2008, there was a high negative correlation between rainfall and Nino 3.4 index, the El Niño-monsoon relation was very strong for 2000-2008 when IOD events were less frequent. Figure 3.24 (c & d), also establish the strong La Niña-monsoon relationship during 2000-2008. Whereas, the relationship was week during 1991-1999.

3.4 Conclusion

During the two decades of the study period 1991-2008, a series of major climatic events were reported. The major positive IOD years were reported as 1994, 1997 and 2006. The years 2007 and 2008 were also recorded as positive IOD years with low intensity and 1994 was a prolonged positive IOD year with its peak phase in October. The strongest event was recorded in 1997, which was strongest El Niño of the Century. The years 1992, 1996 and 1998 were the strong negative IOD years during this period. Of these 1992 was associated with a weak El Niño and 1998 with a strong La Niña. The IOD of 1996 was followed by the La Niña of 1995-1996, which caused the low SST pattern of Arabian Sea during that year, rather than the other negative IOD years.

The wind patterns along the equator as well as in the north Indian Ocean show drastic changes during the IOD events. The climatology illustrates that the zonal winds are mostly westerly throughout the year with stronger magnitudes over the east central equatorial region. The study shows that the wind pattern over the EAS is very responsive to IOD events. The southwest wind pattern is fully developed in July and it sustained till September and in September, the south westerlies weakened and north easterlies are observed in SEAS during the positive IOD years. But all over the EAS except a small area in the southeast, the winds are south westerlies. During October which is the peak phase of IOD, the reversal of wind occurs over SEAS from north easterlies to south westerlies. Whereas during the negative IOD years the southwest winds are well developed in June itself and it sustain only upto July. In early August, the complete reversal of south westerlies to north easterlies occurs.

The variability in SST plays an important role in the meteorological as well as oceanographic processes when compared to other ocean parameters. An attempt has been made to explain the interannual SST trends of EAS during 1991 to 2008 and the role of IOD in modulating the same. During this period, there were three strong positive IOD years (1994, 1997 and 2006) and correspondingly there was an increasing trend in the SST. SST_{max} was greater than 31°C in EAS after 1997-98, which was a strong El Niño year associated with a strong positive IOD. 1999-2000 was the strongest La Niña year and in that year SST showed an obvious decrease from the previous year. There was a weak El Niño during 2006-2007 and a strong La Niña in 2007-2008. Corresponding to this, SST showed an increase in 2007 and a decrease in 2008. The variation of SST_{max} (April-May) for EAS shows anomalous warming in the years followed by a positive IOD year. During spring, intense warm pool is observed associated with the positive IOD years. Whereas negative IOD years are characterized by cold SSTA in EAS. Usually the summer monsoon is characterised by excessive cooling in the region especially due to enormous wind mixing and the prevalence of the coastal upwelling. But in positive IOD years there was a positive SSTA in EAS during summer when compared to the negative IOD years. The fall and winter seasons also show positive SSTA during positive IOD years. The maximum positive SSTA occurs during fall (October) which is the peak phase of IOD events. The subsurface temperature of EAS (25m depth) for four different seasons representing the positive and negative IOD years also highlights the variations in temperature during positive and negative IOD years. The heat content in the upper 70 m of EAS shows the same trend with SST DMI. During the positive IOD year (1994) there is an increase in MLD in the month of September when compared to the negative IOD year (1992). The deviation from the normal pattern of shallow MLD during September 1994 might be due to the domination of north easterlies.

The SSS distribution in the north Indian Ocean shows large spatial variability. During IOD years the salinity anomalies are high in eastern equatorial Indian Ocean. These salinity variations are also appeared in the southern part of EAS during IOD years. During spring (April) the salinity distribution is almost in a similar pattern for both the positive and negative IOD years. The coastal waters of southwest coast of India are having a salinity range of 34.6-35.6 psu during this time. Whereas, during July the high saline tongue (35.6 psu) observed to be extending towards southeast up to 10°N. And the coastal SSS showed a decrease (~34.4 psu) during this month. The fall (October) and winter monsoon (December) seasons are characterized by strong SSS gradient possibly due to the heavy rainfall during the positive IOD years of 1994 and 1997. Intrusion of Bay of Bengal low saline water to the SEAS is observed maximum during the positive IOD years of 1994 and 1997 and is followed by anomalous warming of the upper column. Thus, it can be concluded that, the intensity of warm pool of the SEAS followed by a positive IOD is higher. In positive IOD years the negative anomaly is strong and the intrusion happens earlier than that during the negative IOD years. The reversal of the NEC also supports this intrusion of low saline water very strongly during positive IOD years.

The negative IOD years show a high SWR in the equatorial region. But during positive IOD years it is very less. In the eastern part of the study area SWR is very low during the positive IOD year 1994. Whereas, the pattern is different during 1997 which was a positive IOD year associated with the strongest El Niño. During positive IOD years the SWR is very low during the fall and the subsequent winter monsoon seasons. The LWR also shows considerable north south variation in EAS. The relative changes in SHF are significant in SEAS during the positive IOD years 1994 and 1997. During negative IOD years latent heat loss is more when compared to positive IOD years. During positive IOD years the heat gain is high in SEAS when compared to negative IOD years.

SSHA is the most profound parameter to explain the phenomenon like upwelling and downwelling. Summer monsoon seasons of the negative IOD years are recorded with a low SSH than positive IOD years. During the negative IOD years there are significant changes in winter season in terms of coastally trapped wave propagation, when compared to the positive IOD years. Similar pattern is also observed in the case of D20. As compared to the positive IOD years, the negative IOD years showed an uplift of D20 along the west coast of India especially during summer monsoon and fall. This indicates the upsloping of the upwelling mode Kelvin wave. But in December these isotherms deepened and confined to the coast in negative IOD years. During positive IOD years there is no considerable variability in D20.

In positive IOD years, the equatorial current during summer monsoon is towards west. But in SEAS the zonal current is towards east with very less intensity. In negative IOD years these currents are very strong and are towards east. For spring season, the geostrophic current pattern is almost similar for positive and negative IOD years. During summer monsoon, the currents are towards south along west coast of India. During fall season, the coastal waters of west coast of India showed a current pattern towards north in positive IOD years and towards south in negative IOD years. In winter, during negative IOD years there was a strong geostrophic current flowing towards north which was very much confined to the coast. This phenomenon is not identified during positive IOD years.

Coastal upwelling of southwest coast of India has reflective impacts on the coastal fisheries. During the period 1991-2008, the upwelling intensity in positive IOD years is less when compared to the negative IOD years. The immediate biological response of the coastal upwelling is the primary production and along the SEAS, the most productive season is the summer monsoon. During 1997-1998, which was a strong positive IOD year associated with strong El Niño, the chlorophyll *a* concentration of EAS is found to be less. But during 1998-1999 which was a negative IOD year with strong La Niña the chlorophyll *a* concentration was very high.

During 1991-1999 when the IOD events were frequent, the El Niño - monsoon relationship was weak. But for 2000-2008, there was a high negative correlation between rainfall and Nino 3.4 index. The El Niño-monsoon relation was very strong for 2000-2008 when IOD events were less frequent. La Niña-monsoon relationship during 2000-2008 is strong compared to that of 1991-1999. In the entire study period, the heavy rainfall occurred during the positive IOD events.

Chapter 4

OBSERVED VARIABILITY IN OIL SARDINE AND MACKEREL FISHERY OF SOUTHWEST COAST OF INDIA – STATISTICAL APPROACH

4.1 Introduction

Fisheries play an important role in the world economy and so, exploitation of fishery resources has become a major conservation issue on global scale. Commercial fisheries have been repeatedly blamed for the worldwide decline in fish populations. Marine fishing generates about 1% of the global economy, but coastal and island regions are far more dependent on fishing. About 200 million people worldwide depend on fishing and related industries for livelihood. The quantity of landings is declining in thirteen of the fifteen major marine areas (Garcia and Newton, 1994; Bathal and Pauly, 2008; Zeller *et al*., 2009). Marine fish populations long have been known for extensive variation in landings (Ljungman, 1882). For various fisheries in many parts of the world's oceans the variability in landings has been recognized (Kawasaki and Omori, 1995; Lluch-Cota *et al*., 1999). In the Indian Ocean, there is deterioration in quality caused by decline in the sizes of highly valued species and the move to bulk landings of lower-value species due to climate change (Regier and Baskerville, 1986).

But when considering fish production of India, it has increased more than fivefold since 1950. Special efforts have been made to promote extensive and intensive inland fish farming, modernize coastal fisheries, and encourage deep-sea fishing through joint ventures. These efforts led to the major increase in fishery. At present, India stands seventh place among fishing countries. The South Eastern Arabian Sea experiences strong upwelling during the southwest monsoon period. The Malabar Coast falling under the domain of strong upwelling is the landing area of oil sardine and mackerel. The oil sardine and the Indian mackerel form the major support of Indian pelagic fisheries along the west coast of India (Madhupratap *et al*., 1994). Along the peninsular India 80-95% of the catch of oil sardine and mackerel is from the west coast and the commercial fishery of these species is restricted to 8°N-18°N. These fisheries are shallow water based, the usual depth of fishing confined to the foreshore area within 20-25m depth. Out of these oil sardine is the commercially important fishery of southwest coast of India due to food value and industrial uses for sardine oil, fertilizers, and canning. It contributes significantly to the marine fish landings of India. Like other parts of the world's oceans, this fishery exhibits dramatic fluctuations from year to year. Studies have been conducted to relate this fishery with the variability to seawater temperature, salinity, rainfall, upwelling etc., but they were with limited success (Madhupratap *et al*., 1994; Jayaprakash, 2002; Krishnakumar and Bhat, 2008).

In this chapter, the variability in landings of oil sardine and mackerel are investigated along the southwest coast of India (Fig. 4.1). For this purpose landing data of these species for the period 1991-2008 has been used. To understand the variability in landing of these fishes "Trend Analysis" and "Time Series Analysis' have been conducted. The statistical predication has been validated using observed landing data. The dependence structure in the annual landings of oil sardine and mackerel are also examined.

4.2 Data and Methods

4.2.1 Landing data of Oil sardine and Mackerel

The quarterly landing data of the two major pelagic species (oil sardine and mackerel) for Kerala, Karnataka and Goa representing the southwest coast as a whole are collected from the Central Marine Fisheries Research Institute (CMFRI) and used for the study. CMFRI has been following a suitable sampling design for estimating marine fish landings to arrive at species wise estimates since 1950. The landings are estimated by using a stratified multi-stage random sample design that takes into account landing centres, days and boat net combinations in fishing operations (Srinath *et al.*, 2005). Though the study area covers entire west coast, the highest abundance of Oil sardine and Mackerel mainly occur along the coasts of Kerala, Karnataka and Goa. Hence the landings data of Oil sardine and Mackerel of southwest coast of India, for there period 1991 – 2008 was utilized for the analysis. Time series models are tried to explore the dependence structure in the landings data. The statistical packages Statistical Package for the Social Sciences (SPSS-Version 15.0) and R are used for the data analysis. They provide a wide variety of statistical techniques like linear and non-linear modeling, time-series analysis and clustering.

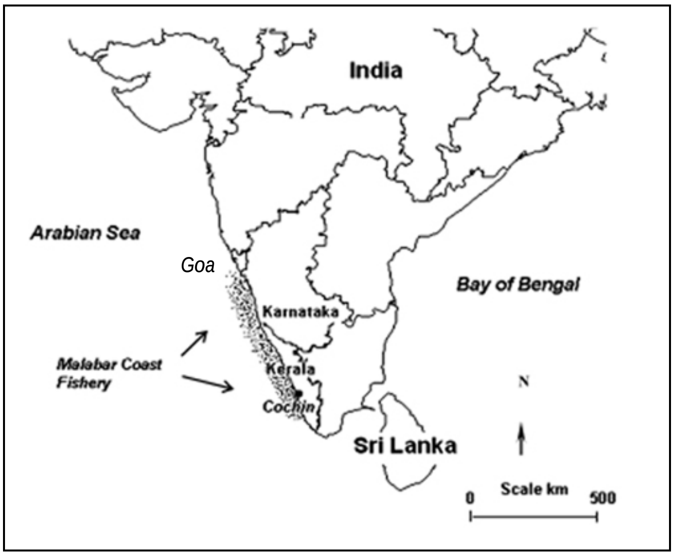


Fig.4.1: Southwest coast of India (Malabar Coast) - Location map

4.2.2 Methodology for the estimation of marine fish landings in India (CMFRI)

The fish landings of the southwest coast of India take place at numerous locations all along the coastline. There are about 1400 landing centres along the coastline of the mainland. The sampling design adopted by the CMFRI to estimate resource-wise/region-wise landings is based on stratified multi-stage random sampling technique, where the stratification is over space and time. Each maritime state is divided into suitable, non-overlapping zones on the basis of fishing intensity and geographical considerations. The number of centres varies from zone to zone. These zones have been further stratified into substrata, on the basis of intensity of fishing. There are some major fishing centres which are classified as *single centre zones* for which there is an exclusive and extensive coverage.

For observation purpose, a month is divided into three groups, each of ten days. From the first five days of a month, a day is selected at random, and the next five consecutive days are automatically selected. From this three clusters of two consecutive days are formed. Normally in a month there will be nine clusters of two days each. From among the total number of landing centers in the given zone, nine centres are selected with replacement and allotted to the nine cluster days. Thus in a month nine landing centre days are observed. The landing centre days are the first stage units in the sampling design. The observation is made from 1200 hrs to 1800 hrs on the first day and from 0600 hrs to 1200 hrs on the second day, in a centre. For the intervening period of these two days, the data are collected by enquiry from 1800 hrs of the first day of observation to 0600 hrs of the 2nd day observation of a landing centre-day, which is termed as 'night landing'. The 'night landing' obtained by enquiry on the second day covering the period of 1800 hrs of the first day to 0600 hrs of the next day are added to the day landings so as to arrive at the landings for one (landing centre day) day (24 hours).

It may not be practicable to record the catches of all boats landed during an observation period, since the number of boats/craft landings is large. A sampling of the boats/craft becomes essential. When the total number of boats landed is fifteen or less, the landings from all the boats are enumerated for catch and other particulars. When the total number of boats exceeds fifteen, the sampling of boats is done in pre-defined manner (Alagaraja, 1984). The fishes are caught by different types of gears. A combination of boat and gear forms the second stage units. From the boats, the catches are normally removed in baskets of standard volume. The weight of fish contained in these baskets being known, the weight of fish in each boat under observation is obtained.

4.2.3 Trend analysis

Time series analysis is applied to determine the main components of the observed chronological data on oil sardine and mackerel landings of the coasts of Kerala, Karnataka, Goa and the southwest coast of India, comprising of these three coasts. The former analysis is used to delineate the two main components namely long term variation or trend and short term variation or the seasonal index after suppressing the cyclical variation along with trend by suitable choice of the period of moving average equal to the period of the cycles if cycles occur. The observed value (O) is assumed to be the multiplicative product of trend (T), seasonal variations (S), cyclical variations (C) and irregular fluctuations (I).

$$O = T * S * C * I \quad \text{--}(1)$$

Trend is estimated by centered moving average method with period equal to 4 (Waymire and Gupta, 1981).

S*C*I = (O*100)/T--(2)

Raw seasonal index, S= average of (S*C*I) average over the years

Correct seasonal index = (Raw seasonal index*100)
Average of the raw seasonal indices-------------(3)

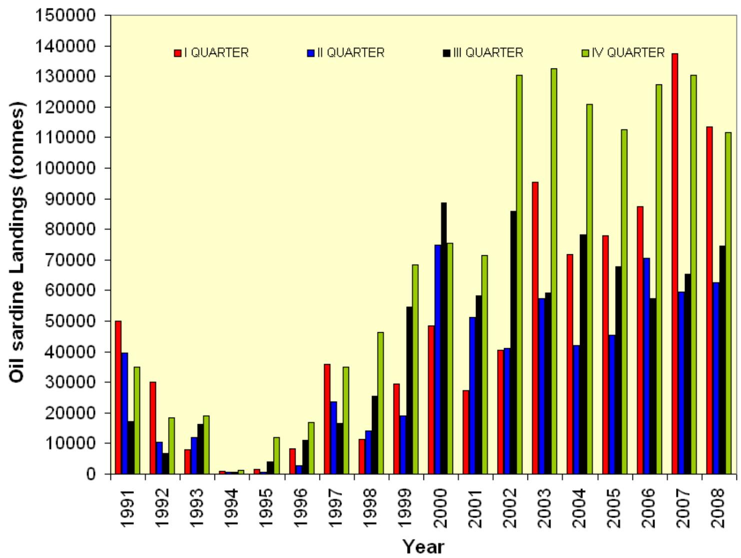
Cycles are removed by proper choice of the period of the moving average and irregular variations are removed by the process of averaging. The observed data, trend and the raw seasonal indices are plotted for each of oil sardines and mackerel in the three coasts and the southwest coast as a whole (Fig. 4.3 – 4.10) and total fish landing in the southwest coast (Fig. 4.11)

4.3 Results and Discussion

4.3.1 Oil sardine and Mackerel landings during 1991-2008

The quarterly landings of oil sardine and mackerel for southwest coast of India during the period 1991-2008 have been presented in the Figure 4.2. It is clearly evident that the contribution of oil sardine to the fishery is more as compared to mackerel. The oil sardine landings showed a decreasing trend from 1991 onwards and reached a lowest catch of that decade in 1994 which was a significant positive IOD year. After 1994 the catch picked up and showed an increasing trend from 1995 onwards. After the occurrence of three consecutive La Niña events 1998-99, 1999-2000 and 2000-01 the oil sardine landings showed a tremendous increase till 2008. The lowest landings of the oil sardine are recorded during 1991-2000 which was a decade with the occurrence of frequent and intense climatic events. However, the mackerel landings showed higher values during this period because mackerel is more susceptible to severe environmental conditions. This abundance of mackerel during this decade caused to predate over the oil sardines in that area led to the collapse of the oil sardine fishery, in addition to the influence of extreme climatic events. This inverse behaviour of oil sardine and mackerel was postulated also by Hornell (1910) and Nair and Chidambaram (1951). They explained this inverse relationship in terms of competing species in a multiple fishery ecosystem. The quarterly landings data of oil sardine shows the maximum catch during Jan-Mar and Oct-Dec (the first and fourth quarters) in most of the years. Instead, mackerel shows maximum catch in the third & fourth quarter. From 1991 to 1994 there was a decreasing trend in oil sardine landings with minimum catch (<5000 tonnes) during 1994.

(a)



(b)

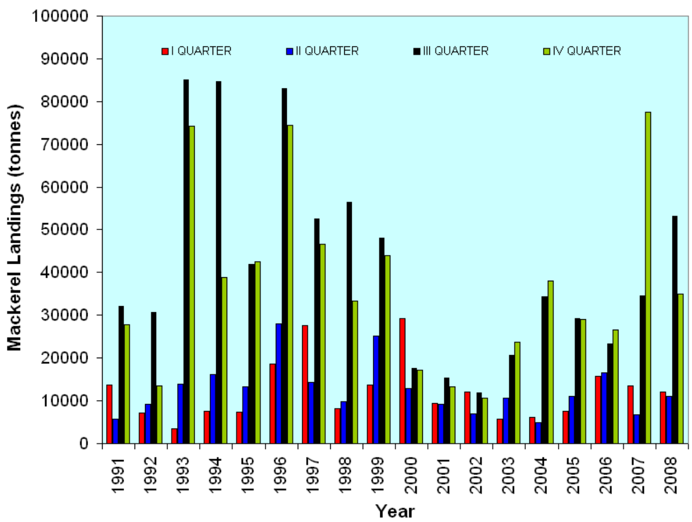


Fig.4.2: Quarterly landings along the southwest coast of India

(a) Oil sardine (b) Mackerel

4.3.2 Trend analysis of Oil sardine and Mackerel landings

The trend analysis of oil sardine landings of Kerala, Karnataka, Goa and the southwest coast are shown in the figures 4.3, 4.4, 4.5 and 4.6 respectively. Oil sardine landings of Kerala show a long term variation during the study period, but it follows a seasonal variation (short term variation) from 2000 onwards. The long term variability observed during the decade 1991-2000 represents the period with severe climatic events. Karnataka and Goa landings also show the same trend of Kerala. When considering the oil sardine landings of southwest coast of India as a whole, it can be seen that the landings follow a long term variation through out the study period and the seasonality is with low variation. The trend of oil sardine landings of southwest coast of India showed a linear increase after the 1994 positive IOD year. The explanations for this statement is appended in Chapter 5 (section 5.3.1).

But mackerel landings show a different pattern from the oil sardine landings of Kerala, Karnataka, Goa and southwest coast (Fig. 4.7 to 4.10). For Kerala coast the mackerel landings show seasonality upto the year 2000 and after that year it was not showing any seasonality. For Karnataka and Goa coasts the seasonal changes in mackerel landings were more. When considering the whole southwest coast, the mackerel landings do not show any long term trend, but it keeps seasonality throughout the study period. Along the southwest coast of India oil sardine landings have a long term variation and the mackerel landings follow a seasonal variation.

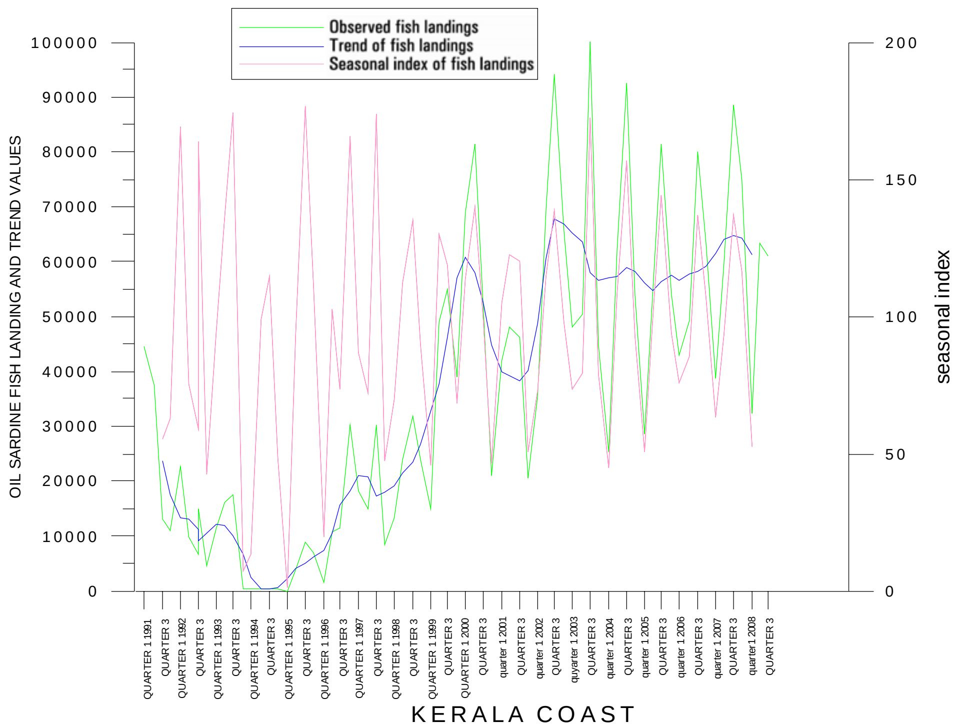


Fig.4.3: Time series components of oil sardine landings of Kerala

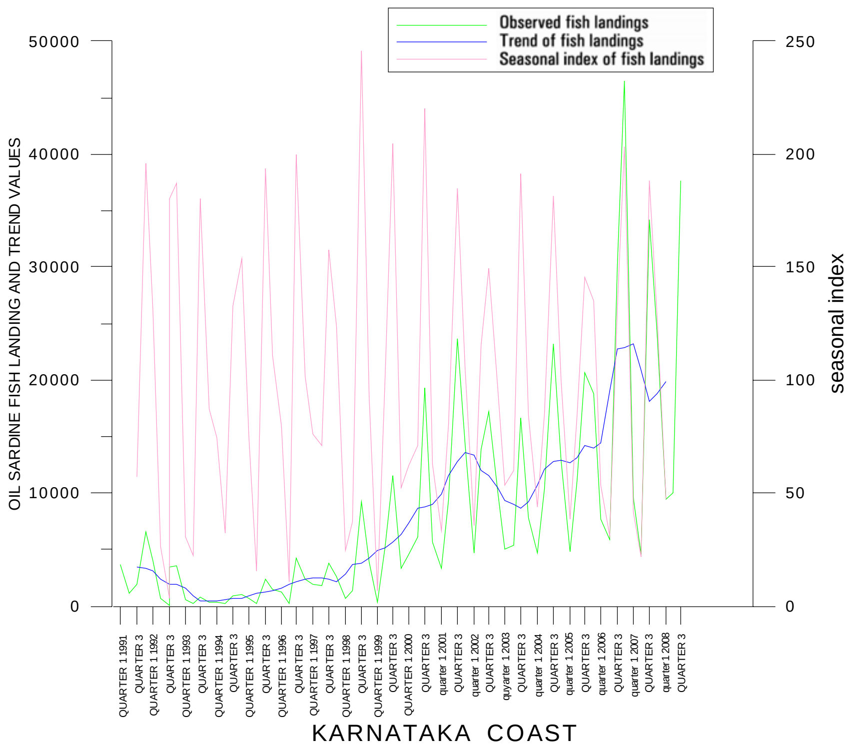


Fig.4.4 Time series components of oil sardine landings of Karnataka

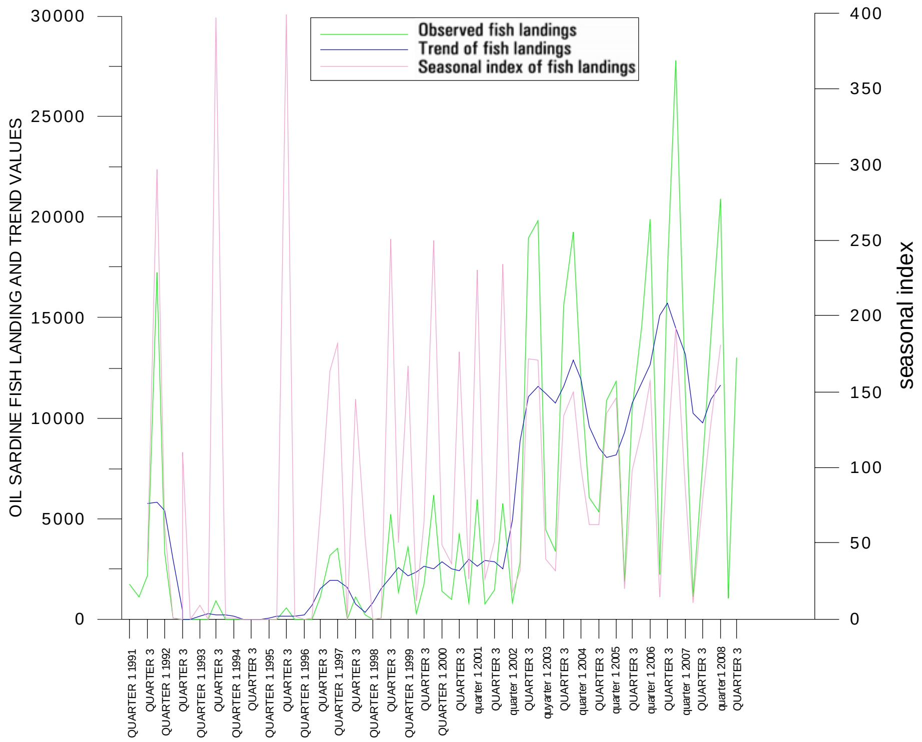


Fig.4.5 Time series components of oil sardine landings of Goa

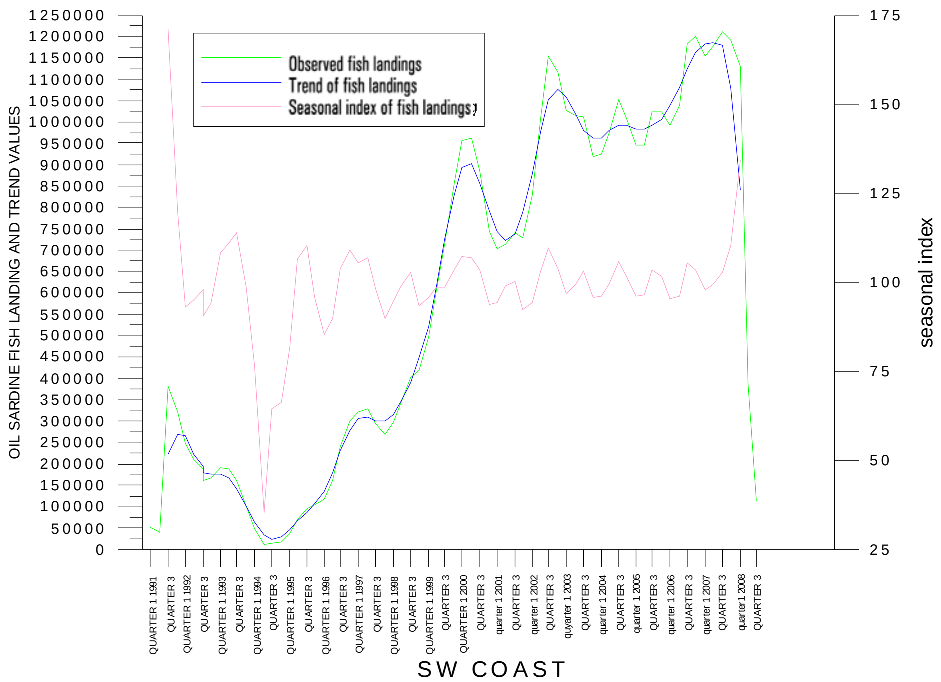


Fig.4.6 Time series components of oil sardine landings of southwest coast of India

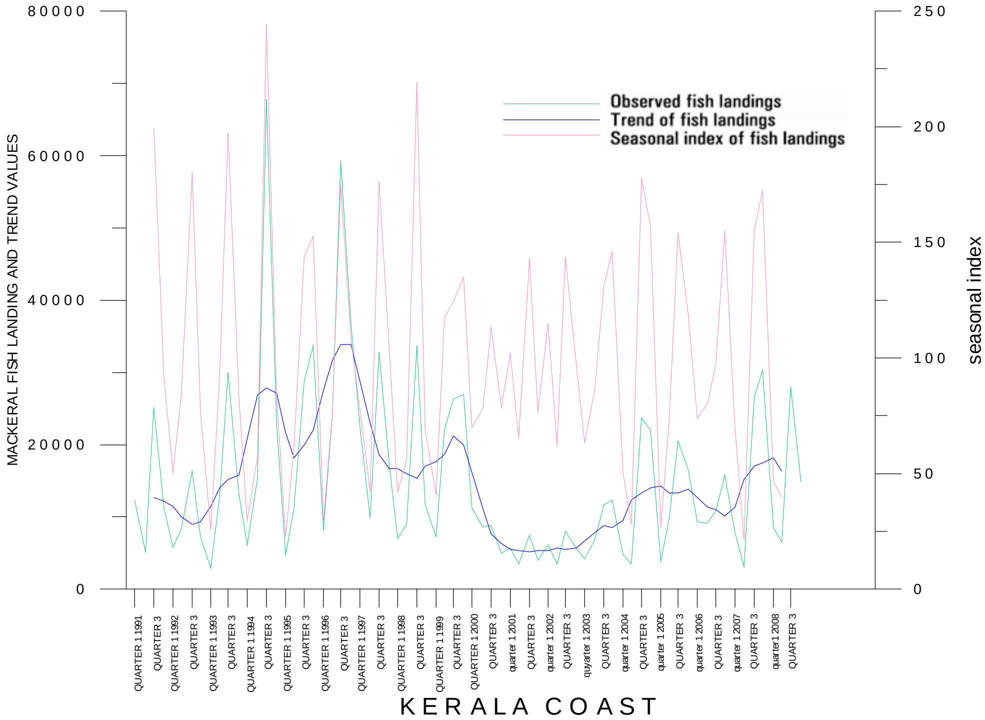


Fig.4.7 Time series components of mackerel landings of Kerala

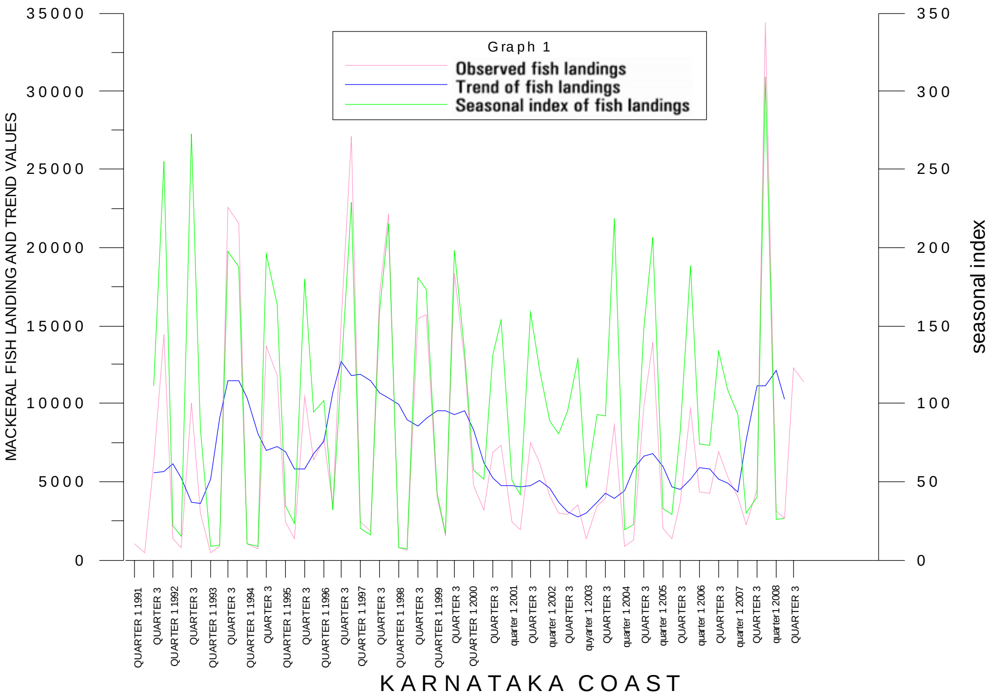


Fig.4.8 Time series components of mackerel landings of Karnataka

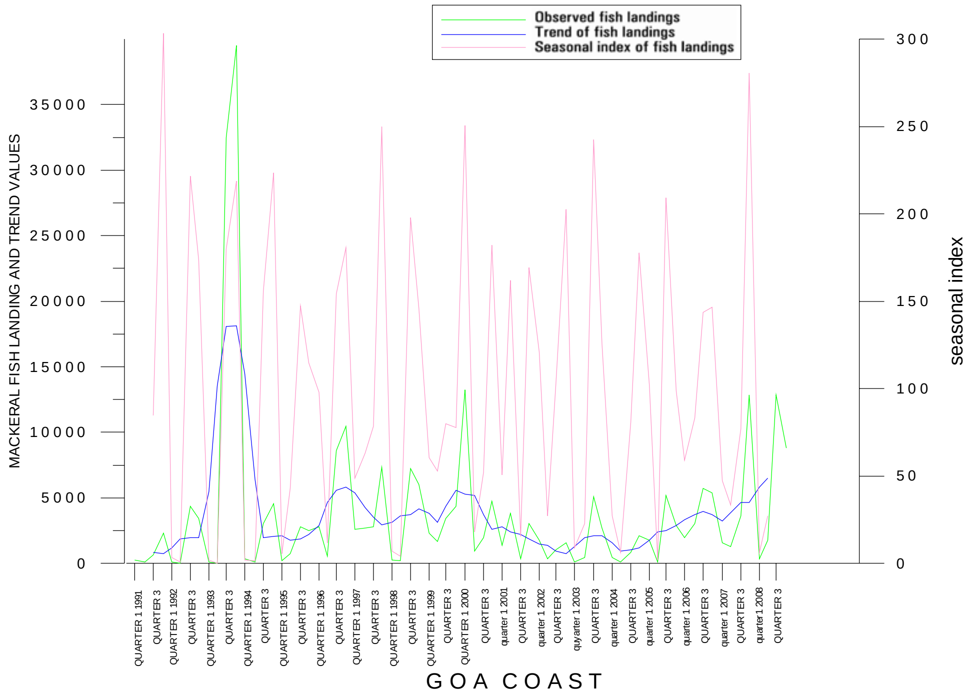


Fig.4.9 Time series components of mackerel landings of Goa

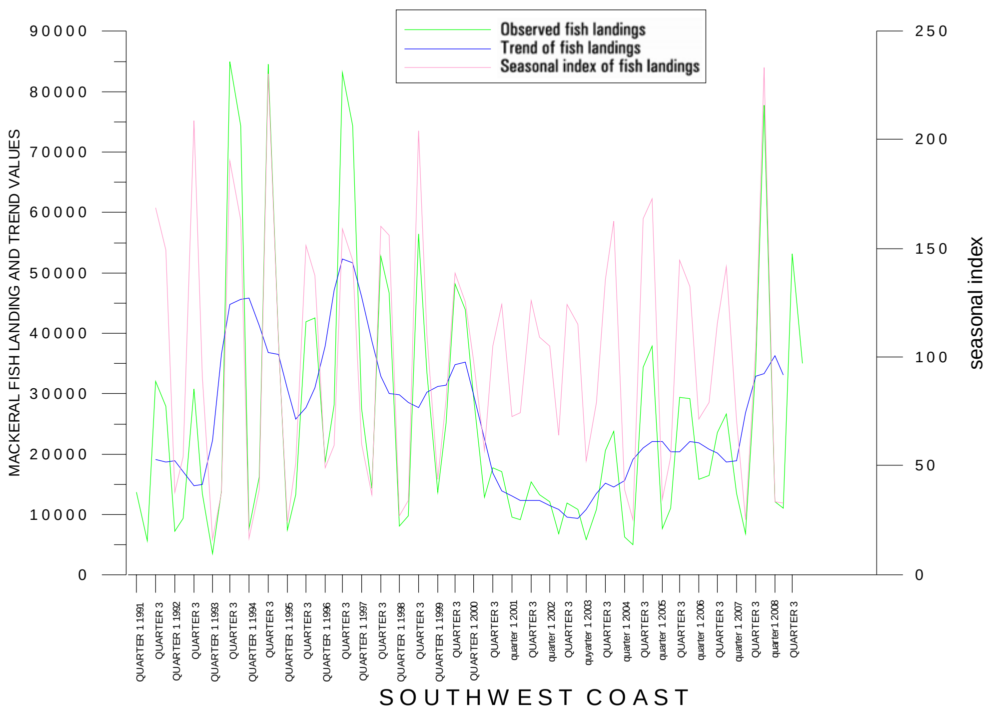


Fig.4.10 Time series components of mackerel landings of southwest coast of India

4.3.3 Modeling and Prediction

The marine fishery in India is a multi-species multi-gear system and the analysis of such a complex system is quite tough (Sathianandan and Srinath, 1995). The time series data of fish landings can be analysed by different methods (Box and Jenkins, 1976). Autocorrelation analysis is one of them and it seems to be more appropriate for ecological analysis (Moran, 1953). Here an attempt has been made to study the dependency structure in the landings data of oil sardine and mackerel and also to forecast the landings through time series analysis by fitting a suitable statistical model. The time series analysis has been successfully applied in several fisheries related studies (Jensen, 1976, 1985; Van winkle *et al.,* 1979; Mendelssohn, 1980; Saila *et al*., 1980; Sathianandan and Srinath, 1995).

In the statistical approach, particularly in time series analysis, an Auto-Regressive Integrated Moving Average (ARIMA) model is used. This model is fitted to time series data either to better understand the data or to predict future points in the series (forecasting). It is applied in some cases where data show evidence of non-stationarity, where an initial differencing step (corresponding to the "integrated" part of the model) can be applied to remove the non-stationarity. The model is generally referred to as an ARIMA (p,d,q) model where p, d, and q are non-negative integers that refer to the order of the autoregressive, integrated, and moving average parts of the model respectively.

To visualize the structure of the time series data of annual landings of oil sardine and mackerel for the period 1991 to 2008, the sequence plots of these series have been plotted (Fig. 4.11). From this figure it is clear that there is an increasing trend in oil sardine landings and decreasing trend in mackerel landings. The landing data sets are not stationary; that means there is a quadratic behaviour. Stationarity can be assessed from a run sequence plot and also it can be detected from an autocorrelation plot. The autocorrelation method is important for checking the dependency in time series data, which is the cross-correlation of the data with itself, offset by **N** values.

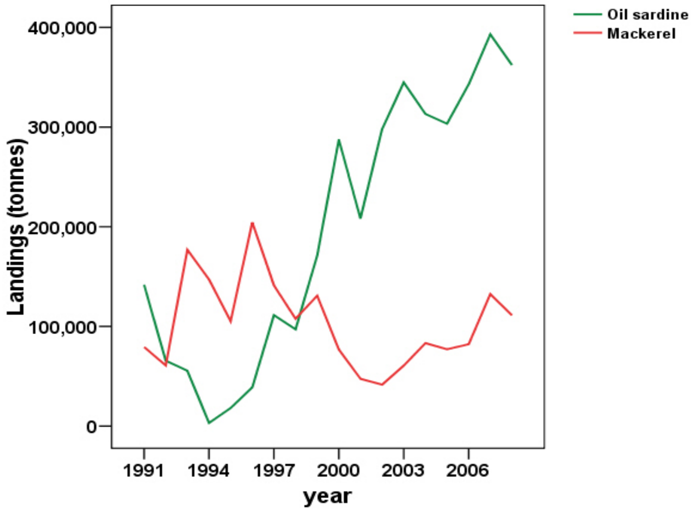


Fig.4.11: Time series plot of Oil sardine (Green) and Mackerel (Red) during 1991-2008

A common estimate of Auto Correlation Function (ACF) is given by:

$$\mathbf{r}_k = \frac{\frac{1}{N}\sum_{t=1}^{N-k}(Z_t - \bar{Z})(Z_{t+k} - \bar{Z})}{\frac{1}{N}\sum_{t=1}^{N}(Z_t - \bar{Z})^2} \text{ ; where } \bar{Z} = \frac{1}{N}\sum_{t=1}^{N} Z_t$$

The lags are **k** = 0,1,2….**k** and **k** is ≤ **N -1**; $\mathbf{Z_t}$ is the value of the time series at time **t.**

Autocorrelation for the oil sardine and mackerel landings are shown in the figure 4.12. The ACF for all lags are significant for oil sardine landings, but in the case of mackerel landings there is no significance in the lags. The

ACF of mackerel has not shown any pattern as it has a random (not autocorrelated) behaviour. Hence further analysis with ARIMA model is not possible in this case as the main focus is to find a mathematical model which provides a plausible description of the dependence structure in the data. The Box-Ljung statistics, which tests the autocorrelation, is also significant for all lags in the case of Oil sardine (Table 4.1a) and not significant for Mackerel (Table 4.1b). The Box-Ljung test evaluates whether any of a group of autocorrelations of time series are different from zero. Instead of testing randomness at each distinct lag, it tests the overall randomness based on a number of lags. The test statistic is;

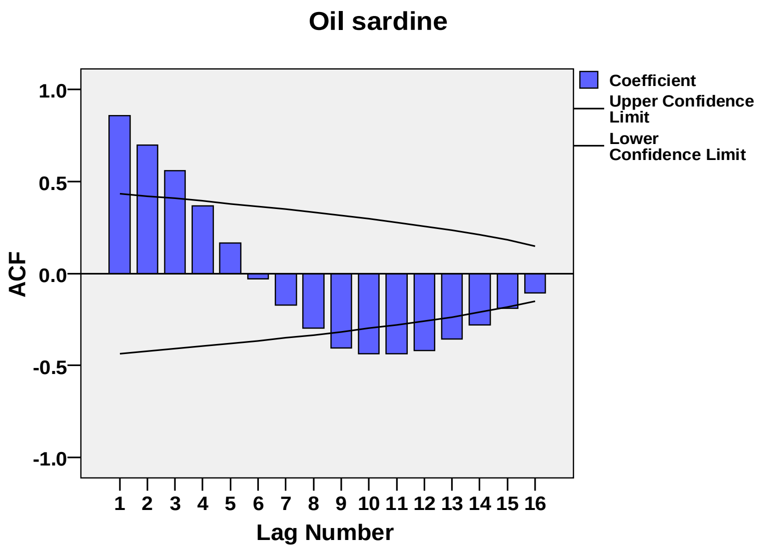
$$Q = n\,(n+2)\sum_{k=1}^{h}\frac{\hat{\rho}_k^2}{n-k}$$

where n is the sample size, $\hat{\rho}_k$ is the sample autocorrelation at lag k, and h is the number of lags being tested. For significance level α, the critical region for rejection of the hypothesis of randomness is

$$Q > \chi^2_{1-\alpha,h}$$

where $\chi^2_{1-\alpha,h}$ is the α-quantile of the chi-square distribution with h degrees of freedom. The Ljung–Box test is commonly used in ARIMA model.

(a)



(b)

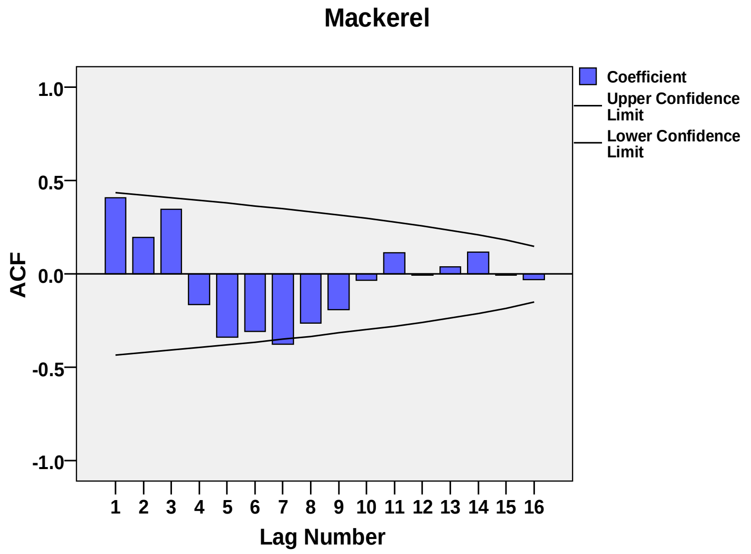


Fig.4.12: Autocorrelation (a) Oil sardine (b) Mackerel

Table 4.1: Autocorrelations from Box-Ljung statistics

(a) Oil sardine (b) Mackerel

Table-4.1a

Autocorrelations

Series: Oil sardine

Lag	Autocorrelation	Std. Error[a]	Box-Ljung Statistic Value	df	Sig.[b]
1	.858	.217	15.592	1	.000
2	.700	.211	26.614	2	.000
3	.561	.204	34.163	3	.000
4	.368	.197	37.644	4	.000
5	.165	.190	38.395	5	.000
6	-.029	.183	38.421	6	.000
7	-.171	.175	39.382	7	.000
8	-.296	.167	42.536	8	.000
9	-.404	.158	49.080	9	.000
10	-.435	.149	57.594	10	.000
11	-.437	.139	67.418	11	.000
12	-.419	.129	77.974	12	.000
13	-.356	.118	87.098	13	.000
14	-.278	.105	94.059	14	.000
15	-.188	.091	98.290	15	.000
16	-.107	.075	100.349	16	.000

a. The underlying process assumed is independence (v noise).

b. Based on the asymptotic chi-square approximation.

Table-4.1b

Autocorrelations

Series: Mackerel

Lag	Autocorrelation	Std. Error[a]	Box-Ljung Statistic Value	df	Sig.[b]
1	.408	.217	3.523	1	.061
2	.197	.211	4.395	2	.111
3	.346	.204	7.273	3	.064
4	-.165	.197	7.976	4	.092
5	-.339	.190	11.151	5	.048
6	-.309	.183	14.021	6	.029
7	-.375	.175	18.613	7	.009
8	-.263	.167	21.106	8	.007
9	-.192	.158	22.586	9	.007
10	-.032	.149	22.633	10	.012
11	.113	.139	23.290	11	.016
12	-.005	.129	23.291	12	.025
13	.039	.118	23.400	13	.037
14	.118	.105	24.645	14	.038
15	-.005	.091	24.648	15	.055
16	-.030	.075	24.810	16	.073

a. The underlying process assumed is independence noise).

b. Based on the asymptotic chi-square approximation.

The behavior of the ACF of Oil sardine (Fig. 4.14a) indicates that the choice of ARIMA model is suitable for fitting the data series (Shumway and Stoffer, 2006). This series have a quadratic trend and the most common way to remove non-stationarity is to difference the time series. Here after differencing two times, the data acquired stationary behavior (Fig. 4.13). The time series plot of first and second difference of the Oil sardine landings is given in Fig. 4.16. The graph shows that the second difference of the data is stationary (mean) even though the variance of the data is not constant.

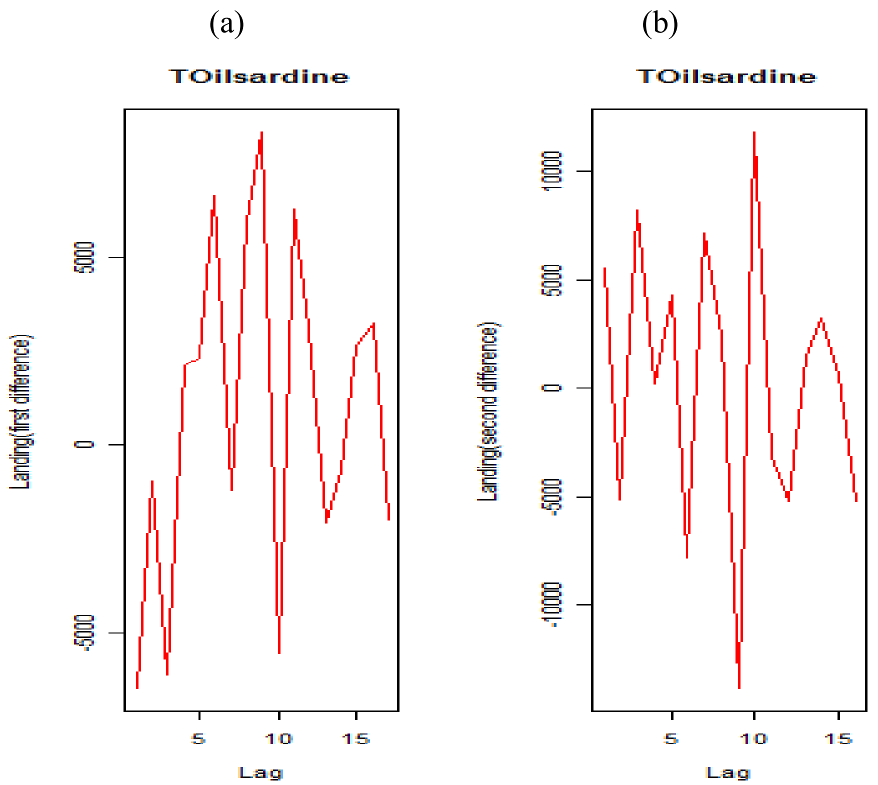


Fig.4.13: The time series plot of transformed data of Oil sardine (a) 1st difference and (b) 2nd difference

Since the second difference of the series is stationary, **d=2** (represents integration) for the ARIMA (p, d, q) model, for identifying the order of autoregressive (p) as well as moving average (q) component of this time series, the ACF and Partial Auto Correlation Function (PACF) of this series has been analyzed. ACF represents the moving average and PACF represents the auto regression part of ARIMA model. The ACF and PACF of the transformed (after differencing) series are represented by figure 4.14a and figure 4.14b respectively. The ACF has spike at lag 1 and all the other lags are not significant so that the moving average component of ARIMA model has an order 1. (**q=1**). The PACF has spike at lag 1 and 2 and at all the other lags are not significant. So the autoregressive component of the ARIMA model has an order 2. (**p=2**). Thus it can be assumed that the model selected for the series is **ARIMA (2, 2, 1)**.

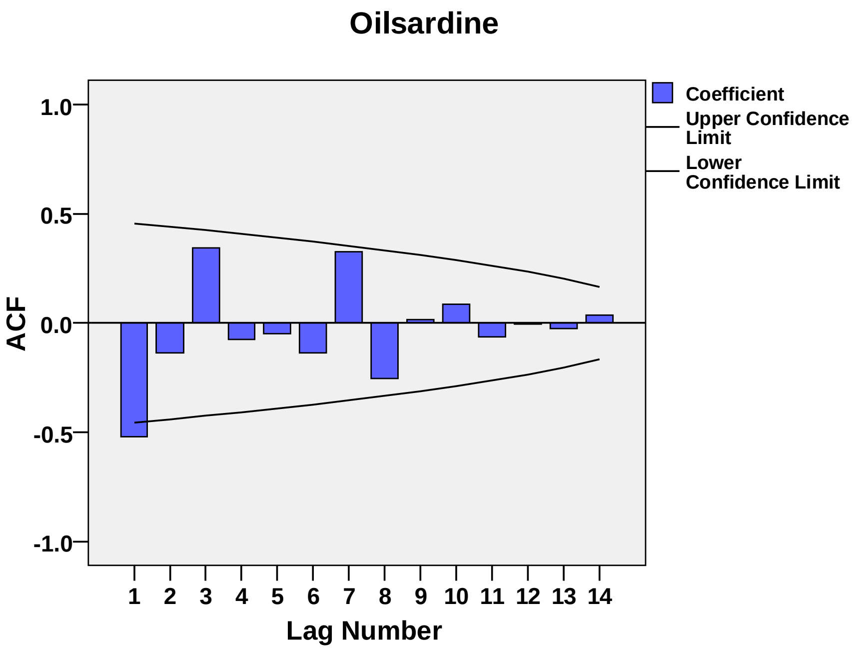


Fig.4.14a: ACF of the transformed series (2nd difference) of Oil sardine [Moving Average]

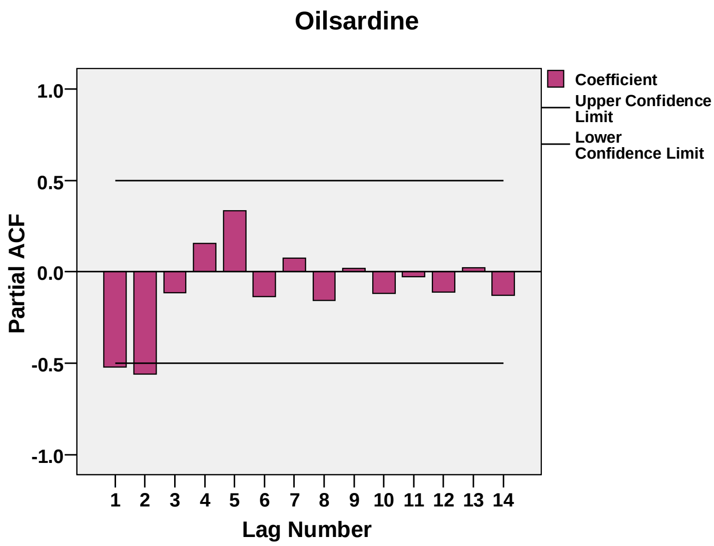


Fig.4.14b: PACF of the transformed series (2nd difference) of Oil sardine [Auto Regression]

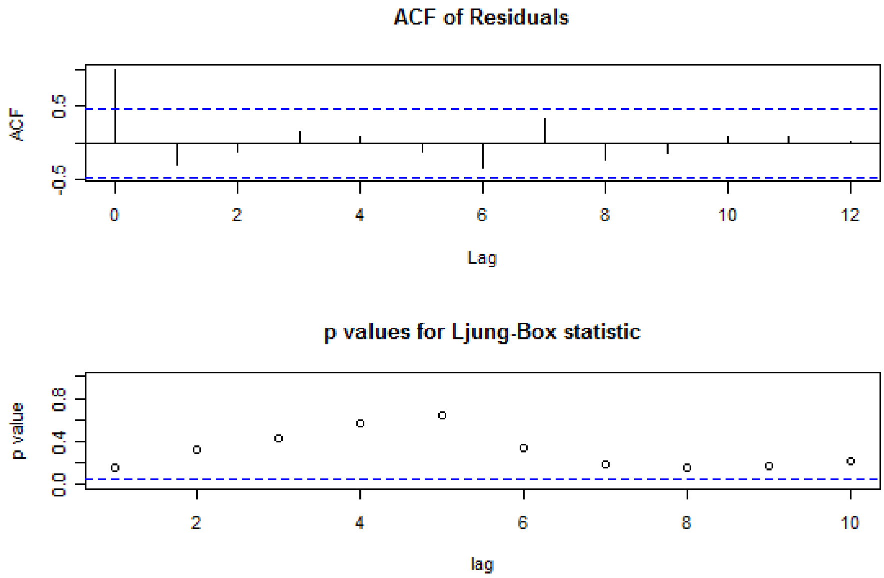


Fig.4.15: ACF of residuals of the model and plot of p values

Then the model diagnostics has been performed to check the validity of the model. The ACF of residuals (errors) and p values of Box-Ljung statistics shows (Fig. 4.15) that the model is well fit for the series, because for a best model fit, p value of residuals should not be significant. That is, for the model with 95% confidence level the p value of residuals should be <0.5. This condition is satisfied with the modeled data of oil sardine landings.

With ARIMA (2, 2, 1) model, the oil sardine landings have been predicted for the period 1991–2008. Figure 4.16 represents the sequence plot of observed as well as predicted landings of oil sardine. The model predictions are in general agree with observed data and the predicted values and the observations are highly correlated (R=0.946, P<0.001). The scatterplot between the observed and predicted landings is given in the Figure 4.17, which also shows the linear regression between the two. The coefficient of determination R^2, which shows the proportion of variability in a data set, has been ranges from 0 to 1. Here it is very high (0.90). Approximately 90 percent of the variation in the predicted landings can be explained by the observed landings. The remaining 10 percent can be explained by the unknown parameters. R^2 value provides a measure of how well future oil sardine landings are likely to be predicted by the model.

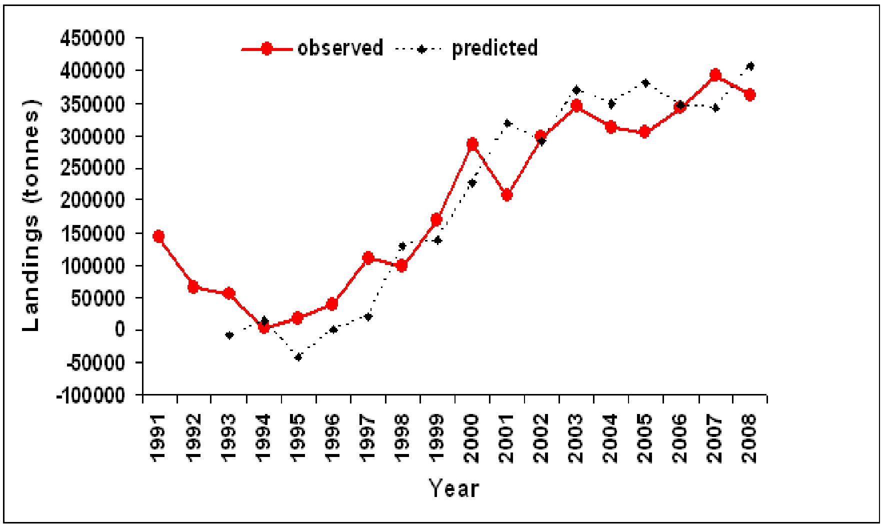


Fig.4.16: Observed and Predicted landings of Oil sardine

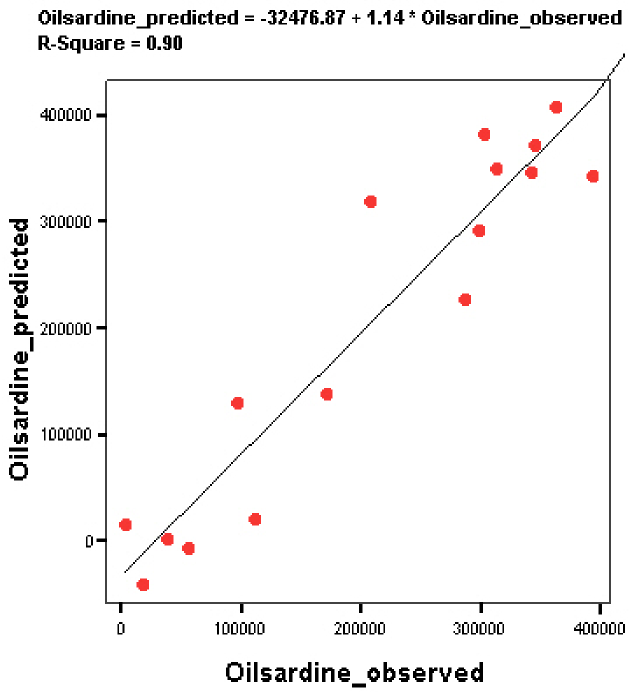


Fig.4.17: Scatterplot of the observed landings against predicted landings

The Normal quantile-quantile plot (i.e., Normal Q-Q plot) graphically compares the distribution of a given variable to the normal distribution (represented by the straight line). Figure 4.18 represents the Normal Q-Q plot of the residual from the prediction and it did not show any evidence of departure from normality, supporting the inference made with the model.

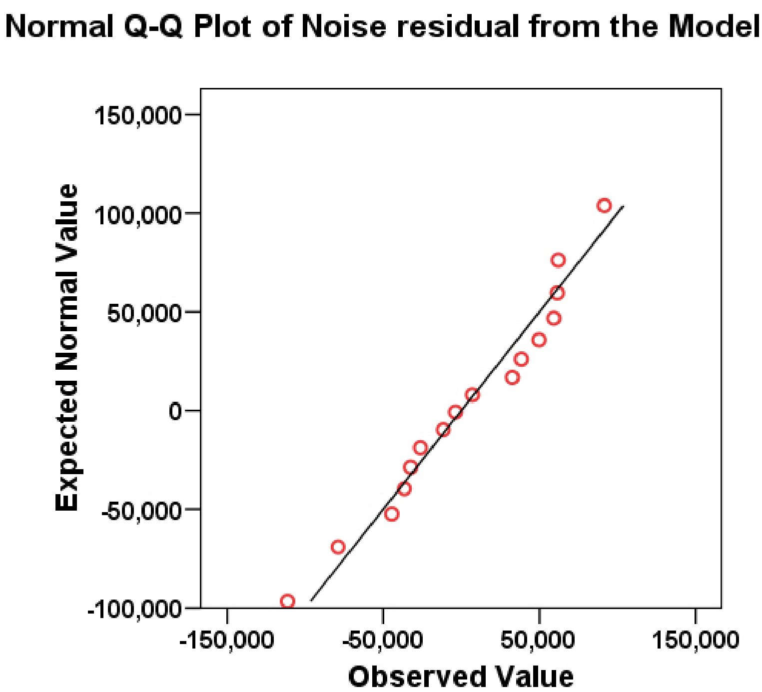


Fig.4.18: Normal Q-Q plot of residuals from the predicted model

4.3.4 Relationship between Oil sardine and Mackerel

The cross correlation between landings of oil sardine and mackerel for the period 1991-2008 has been plotted (Fig. 4.19). From Cross Correlation Function (CCF) it can be seen that there is a strong negative correlation between these two species for the initial lags and it has high significance level. Since the correlation has a peak at lag -1, the current year (corresponding) year oil sardine fishery is negatively affected by the Mackerel fishery of previous year. But at the end of the study period the data shows a positive correlation. The lack of such correlation was also observed by Longhurst and Wooster (1990). The inverse relationship between these two species (oil sardine and mackerel) is also reported by Hornell (1910), Nair and Chidambaram (1951) and Madhupratap *et al*. (1994).

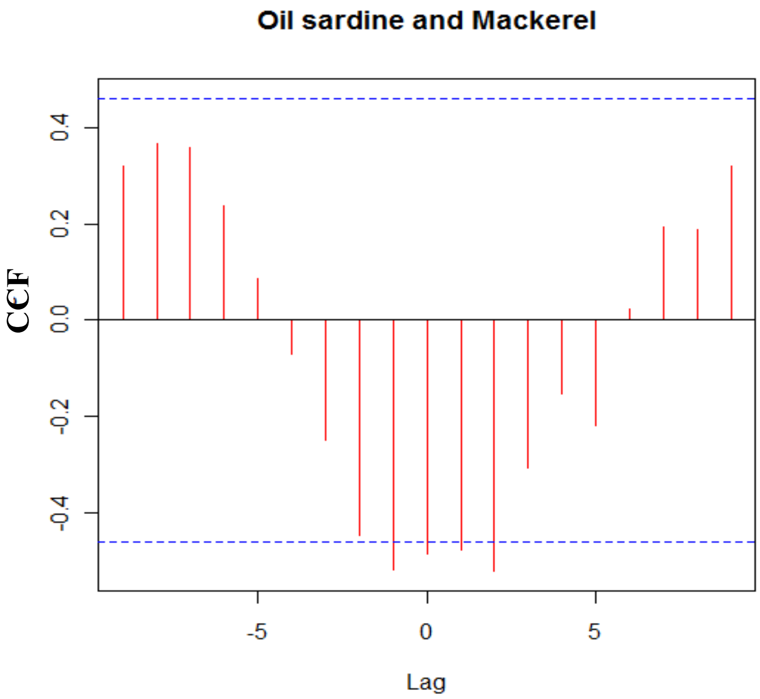


Fig.4.19: Cross correlation of Oil sardine and Mackerel

4.4 Conclusion

The trend analysis of oil sardine and mackerel landings of southwest coast of India (Kerala, Karnataka, Goa) has been conducted for getting the seasonal as well as long term variations during the study period. When considering the Oil sardine landings of southwest coast of India as a whole, it can be seen that the landings follow a long term variation throughout the study period and the trend shows a linear increase after the 1994 positive IOD year. But mackerel landings show a different pattern from the oil sardine landings. The mackerel landings do not show any long term trend, but it keeps seasonality throughout the study period. Along the southwest coast of India oil sardine landings have a long term variation and the mackerel landings follow a seasonal variation.

The dependence structure in the annual landings of oil sardine and mackerel were studied. Oil sardine landings showed a systematic trend while the mackerel landings showed a random behavior throughout the study period. The dependence in oil sardine landings is modeled by ARIMA (2,2,1) and has been used to predict the landings of oil sardine. The forecast of oil sardine landings has been done for the period 2006-2008 using this model. Mackerel did not show any pattern and so the analysis with ARIMA model seems to be difficult in the case of mackerel. The relationship between the landings of oil sardine and mackerel has also been studied. It suggests that the oil sardine and mackerel has a significant negative correlation with 95% confidence level during the study period. Moreover, during the end of the period of study the landings of oil sardine and mackerel show the same trend.

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Chapter 5

INFLUENCE OF ENVIRONMENTAL PARAMETERS ON FISHERY

5.1 Introduction

Environmental factors contribute to the population dynamics and abundance of marine fishery. The relationships between weather, ocean conditions and the fish behaviour, result in the variability of fish catch. These relationships need not necessarily be always direct. The fish search for and select a certain optimum combination of physical and biological conditions in the environment. Temperature is a major factor for analysing the fish occurrence and behaviour. It is not only a factor for analysing the fish, but it indicates indirectly several other processes in the ocean such as mixing, currents, upwelling etc, all of which affect fishery resources. Many fishes respond to currents, their convergences, divergences and large scale eddies, which result in upwelling/downwelling. For getting the complete understanding of the complex interactions between fishery and its affecting factors, a much closer collaboration between the physical, biological and statistical economic sciences is needed. The relation between the fish and its environment is complex indeed.

Influence of physical processes on temporal fluctuations in landings has been studied by Longhurst and Wooster (1990), Lluch-Cota *et al*. (1999) and Madhupratap *et al*. (2001a). There are some studies which relate fishery and climate factors such as precipitation, temperature (Murty and Edelman, 1970; Lluch-Belda *et al*., 1991; Xu and Li, 2002b; Joseph and Jayaprakash, 2003; Norton and Mason, 2005; Suda *et al*., 2005), human exploitation

(Myers *et al*., 1996; Cook *et al*., 1997) or biotic factors including density-dependent survival and growth due to competition (Sundby *et al*., 1989; Myers and Cadigan, 1993; Stenseth *et al*., 1999; Lorenzen and Enberg, 2002; Xu and Li, 2002a).

This chapter summarizes briefly some of the effects of environment on the landings of oil sardine and mackerel during 1991-2008. The correlation between these species and environmental parameters along the coastal waters of southwest coast of India are established here. The more relevant parameters which influence the fishery are sorted out. The impact of IOD on oil sardine and mackerel landings has also been established.

5.2 Data & Methods

Oil sardine and mackerel ladings data are used to establish the correlation with environmental parameters. From the quarterly data sets the annual data from July to next June has been taken (the third and fourth quarters of the corresponding year and first and second quarters of next year) to represent the fishery which starts after every summer monsoon season. The seasonal landings data from October to March (fourth and first quarter) also are used for the correlation study as it represents the period of maximum catch as well as the period of peak IOD events.

Environmental information corresponds to two different geographic scales: regional data including summer monsoon rainfall and upwelling index and large-scale indices such as DMI and Nino 3.4 index. Additionally the oceanographic parameters such as SST, SSS and SSH were used to establish a relationship between fishery and environment. The sources of all the environmental parameters are explained in the third chapter. The oceanographic data has been averaged over 74-78°E and 8-15°N (coastal waters of southwest coast of India).

The statistical analyses have been done with SPSS (Ver. 15.0). To examine the possible relationship between fishery and the environment, the correlations are worked out between time series of fish landings and averages of environmental variables of that region for a time period of October to March. The upwelling index from LTA has been taken as an average from June to September (summer monsoon). SMR of Kerala and Coastal Karnataka has been added together for correlating with fish landings of the southwest coast. The fishery response due to the changes in environmental factors is analyzed with the regression analysis. Since all the environmental parameters are closely interlinked, the multiple regression analysis on these parameters altogether is not possible. Hence the linear regression analysis method has been preferred in this study. Linear regression typically uses the least squares method to determine which line best fits the data (Bowerman *et al.*, 2005). R^2 is a measure of how well the data points match the resulting line.

5.3 Results & Discussion

5.3.1 Influence of environmental parameters on Oil Sardine fishery

Figure 5.1 and figure 5.2 represent the interannual variability of oil sardine landings with respect to the above mentioned environmental parameters. From these figures it is clear that oil sardine has a negative correlation with SSH and SMR and a positive correlation with SST, SSS and Upwelling Index (UI). The increase in the magnitude of positive DMI during the study period shows a decrease in oil sardine landings. Since the increase in DMI represents the positive IOD years where there is a hike in SSH during fall and winter monsoon months and deepening of MLD. This MLD variation can be considered as the reason for the decrease in oil sardine landing during this period. Fishes are highly migratory with respect to the deepening and shoaling of MLD. During the positive IOD years the coastal waters of southwest coast of India the upwelling intensity during summer monsoon months is less (explained in section 3.3.2.7) as compared to the other years. Also the rainfall is more in positive IOD years which affect the fishery in its larval stage. During intensive rainfall, the eggs and larvae of oil sardine are getting washed out. The low primary production in this area during the positive IOD years inversely affects the fish population in that region. SST and SSS also show a direct relationship with the oil sardine fishery.

The increase in the magnitude of negative DMI during the study period shows an increase in oil sardine landings. In negative IOD years during the fall and winter monsoon months, there is a lowering of SSH and cause shoaling of MLD. During the summer monsoon months of negative IOD years the upwelling intensity is more and cause maximum primary production. These conditions favored a good fishery during these years.

The correlation (Pearson) coefficients between environmental parameters and oil sardine fishery are shown in Table 5.1. The relation between oil sardine landings and the environmental parameters can be represented by scatter plots. Results of linear regression analysis between oil sardine landings and the environmental parameters which have significant correlation coefficient are shown in Table 5.2. The R^2 obtained for oil sardine landings with different environmental parameters (SST, SSS, UI, SSH and SMR) are shown in figure 5.3. All the positive correlations are aligned in the left panel and the negative correlations are in right panel. SST, SSS and UI show positive correlation with oil sardine landings and negative correlation with SSH and SMR. Among which SSH shows a maximum correlation (R = -0.765) with oil sardine fishery. As SSH increases the MLD deepens and which badly affect the oil sardine fishery.

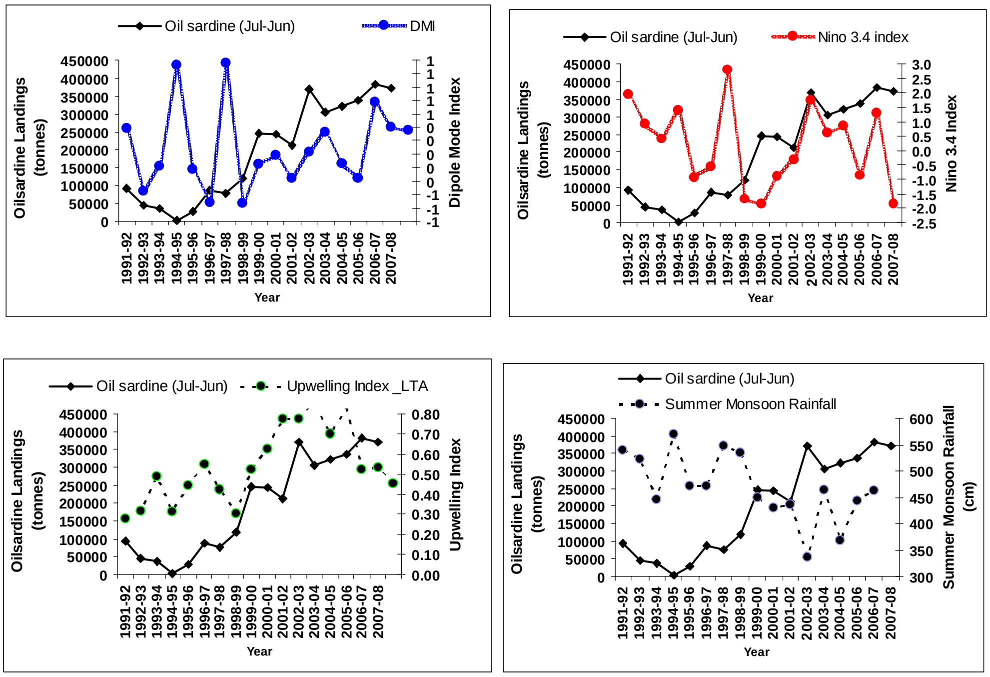

Fig. 5.1: Interannual variability of oil sardine landings with DMI, Nino3.4 Index, UI and SMR

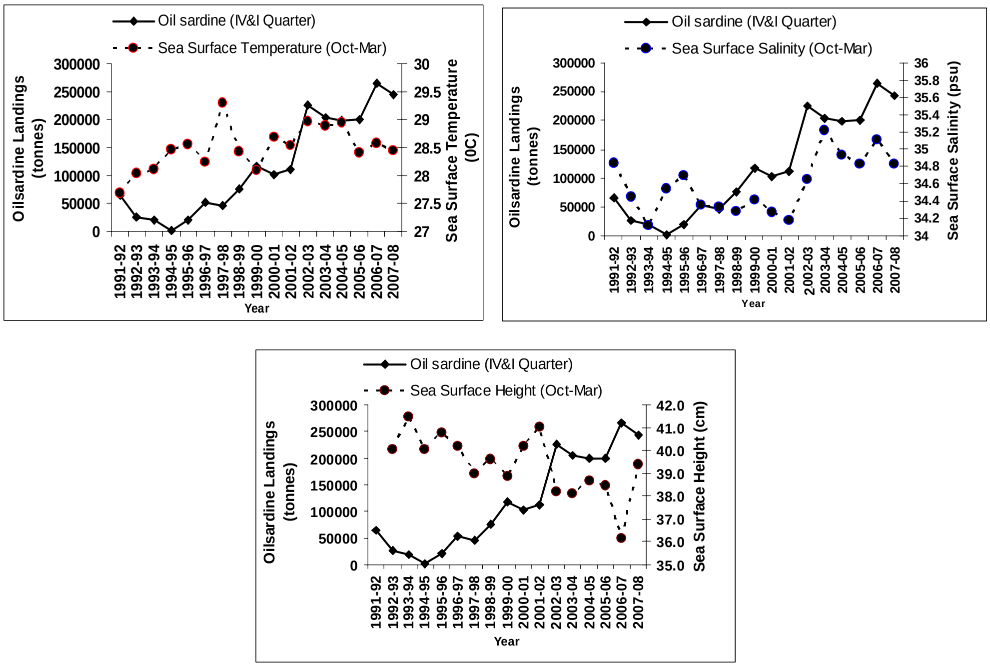

Fig. 5.2: Interannual variability of oil sardine landings with SST, SSS and SSH

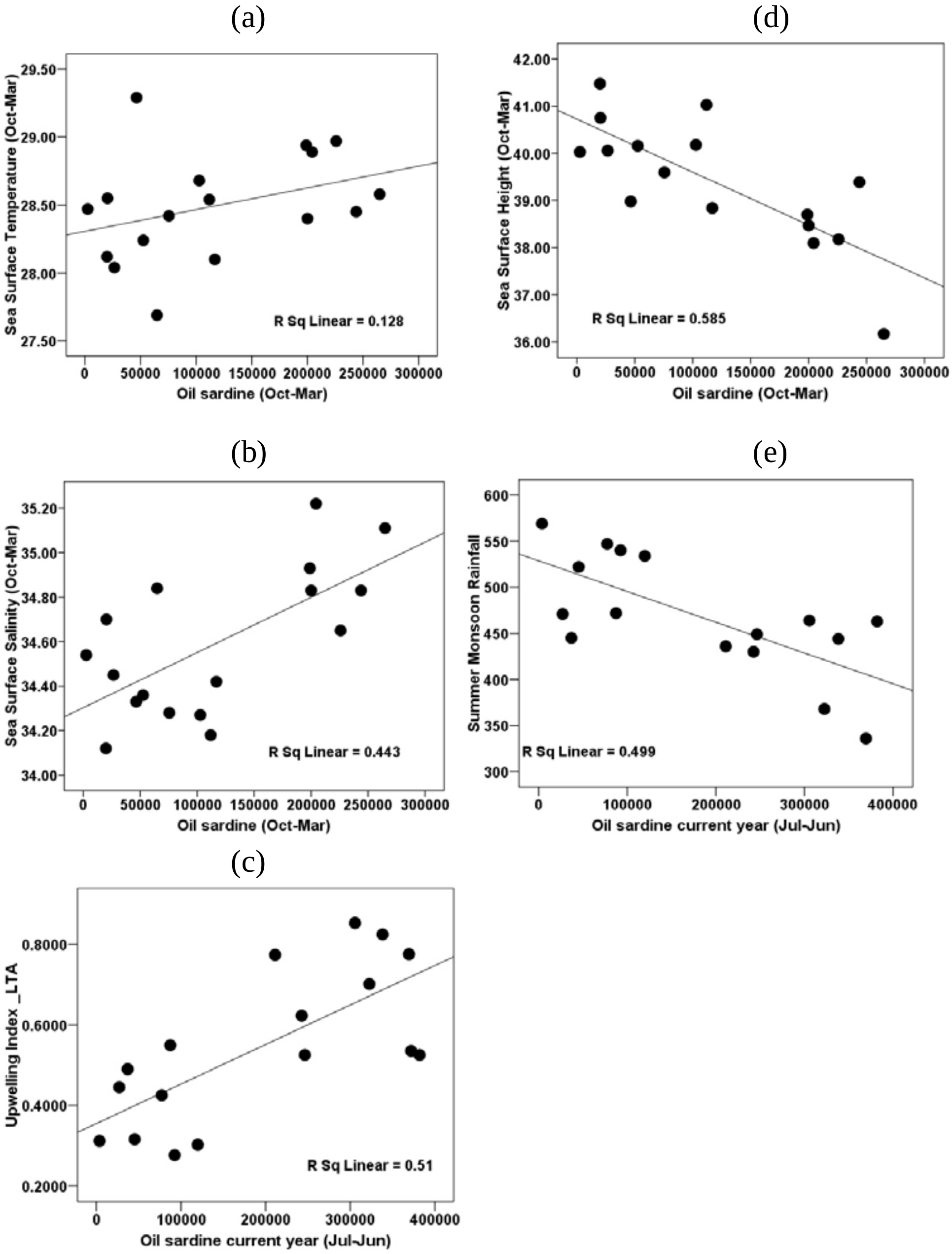

Fig. 5.3: Scatter plot between oil sardine landings and

(a) SST (b) SSS (c) UI (d) SSH (e) SMR

Table 5.1: Correlation coefficients between Oil Sardine landings and environmental parameters

Variables	Pearson Correlation Coefficients		
	Oil Sardine (Oct-Mar)	**Oil Sardine current year (Jul-Jun)**	**Oil Sardine next year(Jul-Jun)**
SST	0.357	0.358	0.450
SSS	0.665**	0.559*	0.414
UI	0.657**	0.714**	0.752**
SSH	-0.765**	-0.709**	-0.629*
SMR	-0.642**	-0.706**	-0.579*

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 5.2: Regression analysis of Oil Sardine landings and environmental parameters

Dependent Variable	Independent Variable	Unstandardized Coefficients		Beta	t	Sig.	R2
		B	Std. error				
Oil Sardine (Oct-Mar)	SSS (Oct-Mar)	178495.8	51710.2	0.665	3.452	0.004	**0.443**
	SSH (Oct-Mar)	-52078.4	11729.7	-0.765	-4.440	0.001	**0.585**
Oil Sardine Current Year (Jul-Jun)	UI	520282.6	131628.2	0.714	3.953	0.001	**0.510**
	SWR	-1495.2	400.7	-0.706	-3.732	0.002	**0.499**
Oil Sardine Next Year (Jul-Jun)	UI	537958.9	126092.9	0.752	4.266	0.001	**0.565**
	SWR	-1278.5	480.7	-0.579	-2.660	0.019	**0.336**

NB: B : These are the values for the regression equation for predicting the dependent variable from the independent variable

Beta : These are the standardized coefficients t & Sig. : These are the t-statistics and their associated 2-tailed p-values used in testing whether a given coefficient is significantly different from zero.
The smaller the value of Sig. (and the larger the value of t) the greater the contribution of that predictor

R2 : These are the proportions of variance in the dependent variable which can be explained by the independent variables

5.3.2 Influence of environmental parameters on Mackerel fishery

Figure 5.4 and figure 5.5 represent the interannual variation of the mackerel landings with the environmental parameters. Mackerel shows a negative correlation with SST, SSS and UI and a positive correlation with SSH and SMR. The correlation (Pearson) coefficients between environmental parameters and mackerel fishery are shown in Table 5.3. Results of linear regression analysis performed for mackerel landings and the environmental parameters do not show any significant relation. The R^2 obtained for mackerel landings with different environmental parameters (SST, SSS, UI, SSH and SMR) are shown in figure 5.6. All the negative correlations are aligned in the left panel and the positive correlations are in right panel. So it can be concluded that mackerel fishery is more adaptive to the changes in these parameters as compared to the oil sardine fishery.

Table 5.3: Correlation coefficients between Mackerel landings and environmental parameters

Variables	Pearson Correlation Coefficients		
	Mackerel (Oct-Mar)	Mackerel current year (Jul-Jun)	Mackerel next year (Jul-Jun)
SST	-0.228	-0.285	-0.068
SSS	-0.185	-0.350	-0.017
SSH	0.255	0.407	0.194
UI	-0.188	-0.409	-0.562
SMR	0.126	0.320	0.451

** Correlation is significant at the 0.01 level (2-tailed)
* Correlation is significant at the 0.05 level (2-tailed)

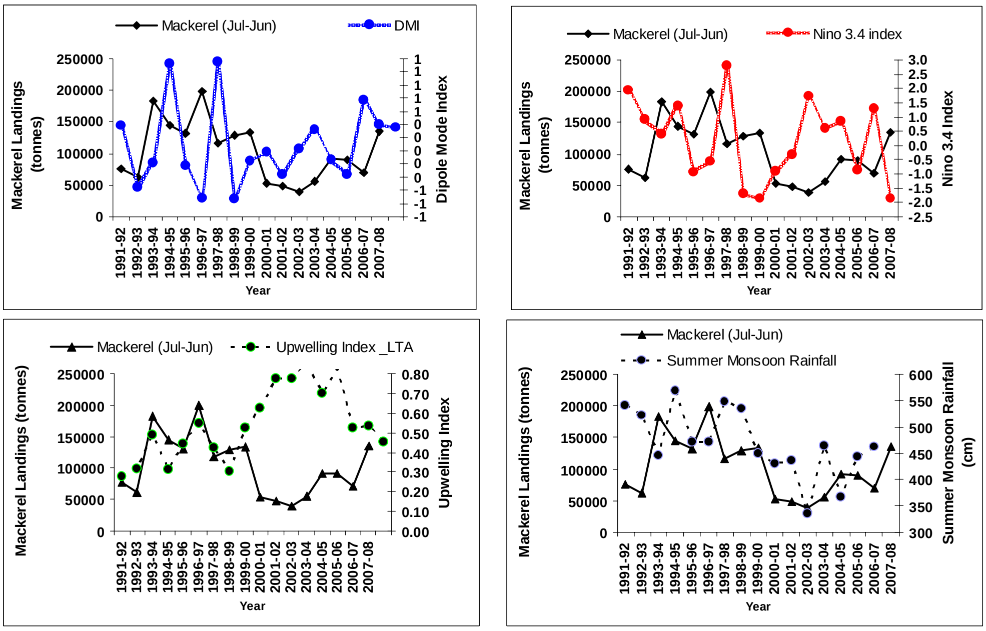

Fig. 5.4: Variability of Mackerel landings with DMI, Nino 3.4 index, UI and SMR

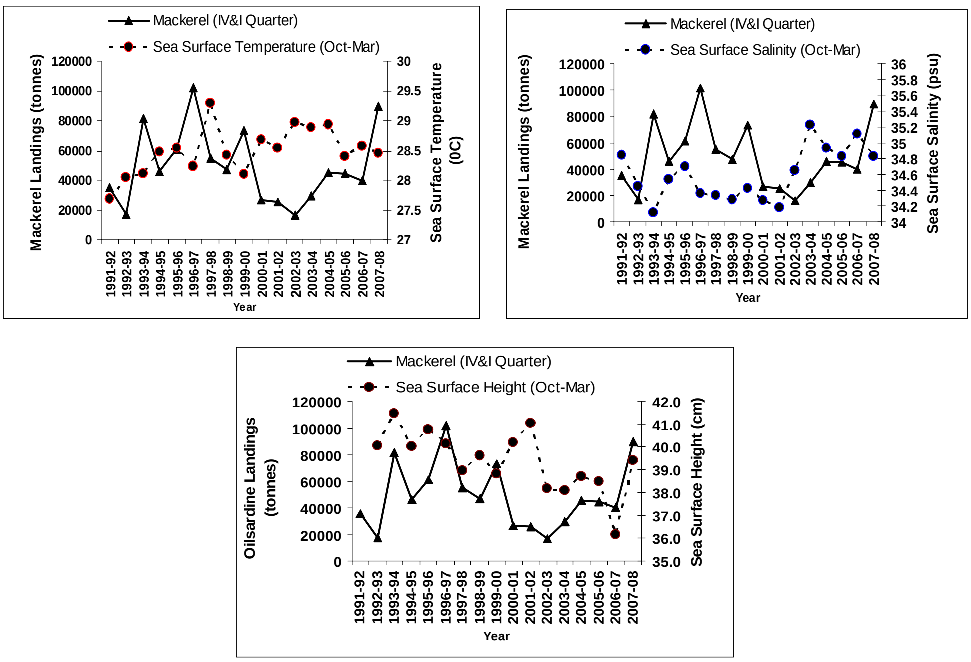

Fig. 5.5: Variability of Mackerel landings with SST, SSS and SSH

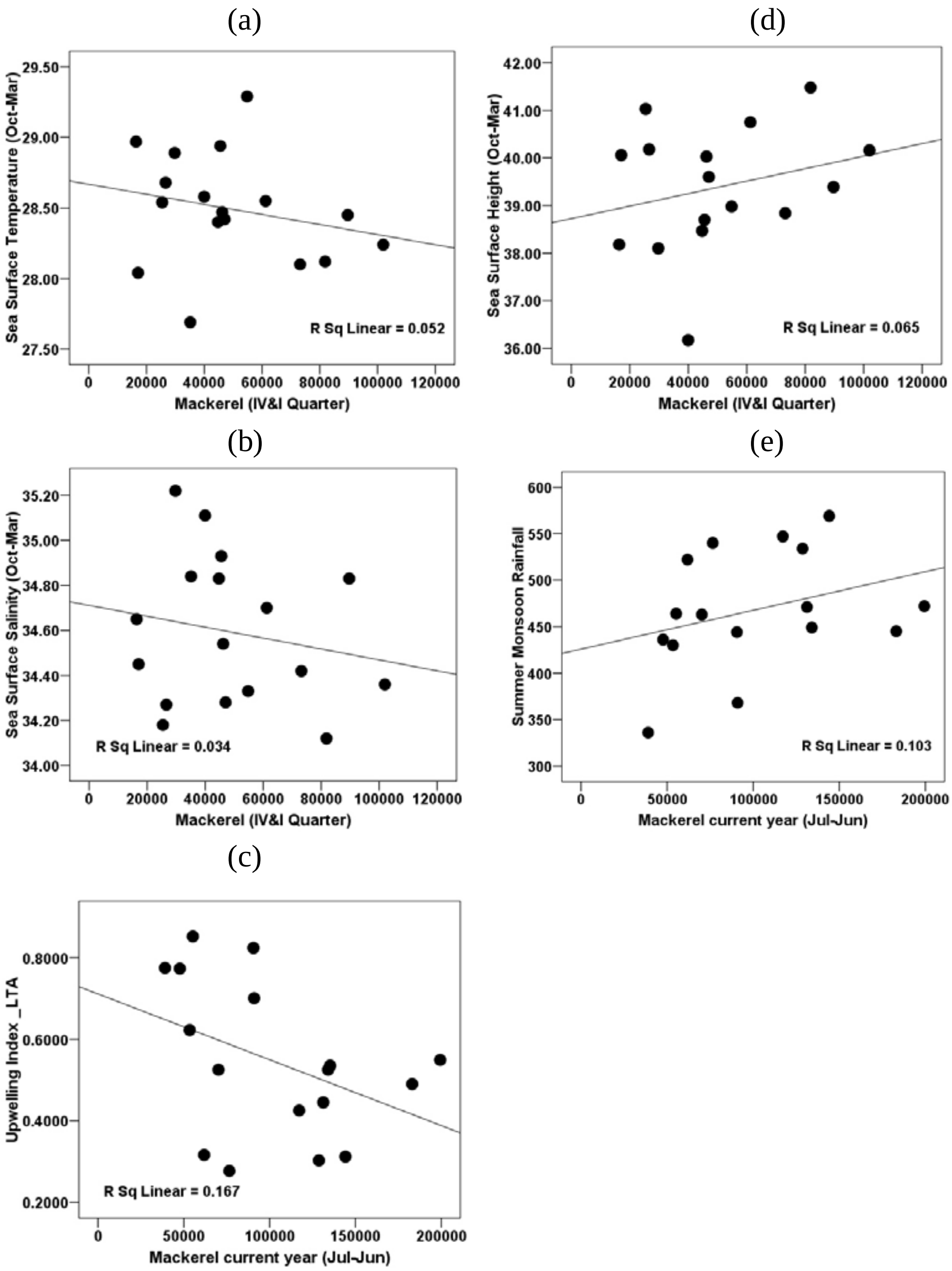

Fig. 5.6: Scatter plot between Mackerel landings and (a) SST (b) SSS(c) UI (d) SSH (e) SMR

5.3.3 Prediction with environmental parameters

The prediction of oil sardine landings has been attempted with the environmental parameters, which shows significant relation with oil sardine landings. Here SSH, UI, SMR and SSS are taken as the significant environmental parameters. Since all the selected parameters are interconnected, it is impossible to predict the oil sardine landings by taking all these parameters together. Hence the analysis has been done independently for all these parameters.

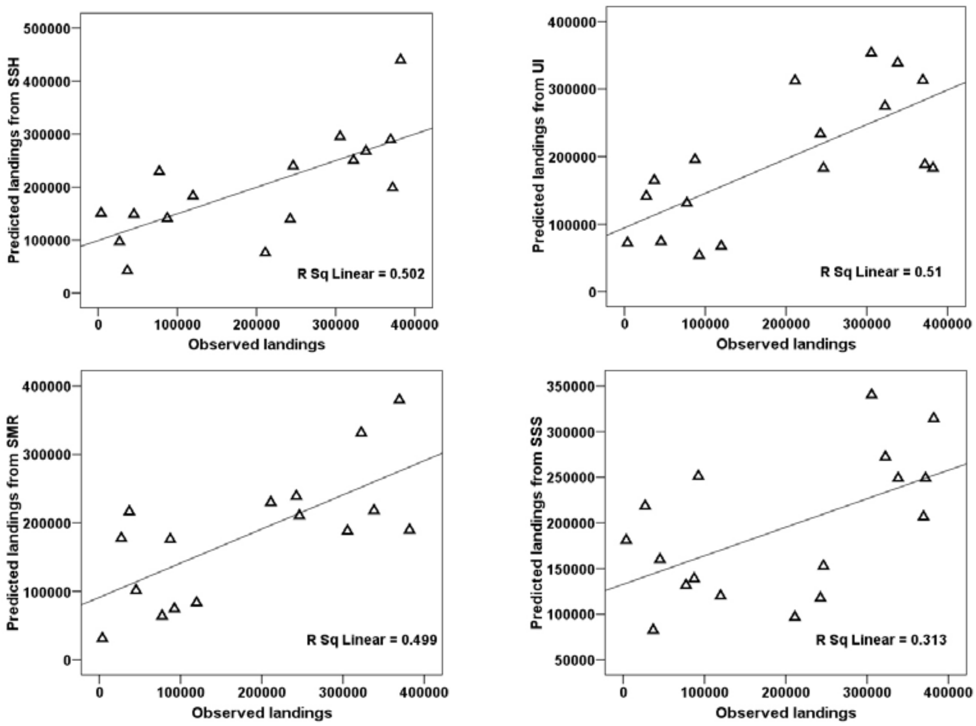

Fig. 5.7: Scatterplot of the observed landings of oil sardine against the predicted landings; from (a) SSH (b) UI (c) SMR (d) SSS

Figure 5.7 shows the relationship between the observed and predicted oil sardine landings. The predicted values and the observations are significantly correlated. The most significant values are from SSH (R =

0.709). Therefore, SSH plays a major role in the variations of annual landings of oil sardine along southwest coast of India. The other parameters such as UI, SMR and SSS also show some roles in the variations in annual oil sardine landings. So it can be concluded that these parameters can be accepted for future prediction of the oil sardine fishery. At the same time this prediction method is not applicable to the mackerel fishery.

5.4 Conclusion

During the positive IOD years the oil sardine landings show drastic changes compared to normal years. The increase in the magnitude of positive DMI shows a decrease in oil sardine landings of southwest coast of India. The landings exhibit a negative correlation with SSH and SMR and a positive correlation with SST, SSS and UI. Fishes are highly migratory with respect to the deepening and shoaling of MLD. The MLD deepening associated with positive IOD years can be considered as one of the reasons for the decrease in oil sardine landings. During the positive IOD years the coastal waters of southwest coast of India shows a less upwelling intensity during summer monsoon months as compared to the other years. The intensive rainfall associated with the positive IOD years affect the oil sardine fishery in its larval stage. The low primary production in this area during the positive IOD years inversely affects the fish population in that region. SST and SSS also show a direct relationship with the oil sardine fishery. The increase in the magnitude of negative DMI shows an increase in oil sardine landings. In negative IOD years during the fall and winter monsoon months, there is a lowering of SSH and cause shoaling of MLD. During the summer monsoon months of negative IOD years the upwelling intensity is more and cause maximum primary production. These conditions favored a good oil sardine fishery during these years.

From the analysis, it can be seen that SST, SSS and UI show positive correlation with oil sardine landings and negative correlation with SSH and SMR. SSH shows a maximum correlation (R = -0.765) with oil sardine fishery. The mackerel landings and the environmental parameters do not show any significant relation.

SSH plays a major role in the variations of annual landings of oil sardine along southwest coast of India. The other parameters such as UI, SMR and SSS also show some roles in the variations in annual oil sardine landings. So it can be concluded that these environmental parameters can be well accepted for the prediction of the oil sardine fishery. In contrary, this prediction method is not applicable to the mackerel fishery.

Chapter **6**

SUMMARY AND CONCLUSION

An attempt has been made to establish the impacts of extreme climatic events on marine environment. Analyses are performed to find the response of the extreme climatic events on physical parameters in the ocean and how these changes affecting the fishery of that region. The major climatic events affecting the tropical oceans are ENSO and IOD. The study mainly concentrated on the impacts of IOD on fisheries of the SEAS. The Oil Sardine and Mackerel landings of the southwest coast of India (Kerala, Karnataka and Goa) have been taken as the fishery data, as these two species form the mainstay of Indian pelagic fisheries along west coast of India.

During the two decades of the study period 1991-2008, a series of major climatic events were recorded. The major positive IOD years reported were 1994, 1997 and 2006. The strongest event was recorded in 1997, which was strongest El Niño of the Century. The study shows that the wind pattern over the EAS is very responsive to IOD events. The southwest wind pattern is fully developed in July and it sustained till September and in September, the south westerlies weakened and north easterlies are observed in SEAS during the positive IOD years. During October which is the peak phase of IOD, the reversal of wind occurs over SEAS from north easterlies to south westerlies. Whereas during the negative IOD years the southwest winds are well developed in June itself and it sustain only upto July. In early August, the complete reversal of south westerlies to north easterlies occurs. The SST variability plays an important role in the meteorological as well as oceanographic processes. The variation of SST_{max} (April-May) for EAS shows anomalous warming in the years followed by a positive IOD year.

During spring, intense warm pool is observed associated with the positive IOD years. Whereas negative IOD years are characterized by cold SSTA in EAS. During the positive IOD year (1994) there is an increase in MLD in the month of September when compared to the negative IOD year (1992) along the SEAS.

During IOD years the salinity anomalies are high in eastern equatorial Indian Ocean. These salinity variations are also appeared in the southern part of EAS during IOD years. During spring (April) the salinity distribution is almost in a similar pattern for both the positive and negative IOD years. Whereas, during July the high saline tongue (35.6 psu) observed to be extending towards southeast up to 10°N. And the coastal SSS showed a decrease (~34.4 psu) during this month. The fall (October) and winter monsoon (December) seasons are characterized by strong SSS gradient possibly due to the heavy rainfall during the positive IOD years of 1994 and 1997. Intrusion of Bay of Bengal low saline water to the SEAS is observed maximum during the positive IOD years of 1994 and 1997 and is followed by anomalous warming of the upper column. Thus, it can be concluded that, the intensity of warm pool of the SEAS followed by a positive IOD is higher. In positive IOD years the negative anomaly is strong and the intrusion happens earlier than that during the negative IOD years. The reversal of the NEC also supports this intrusion of low saline water very strongly during positive IOD years.

The relative changes in SHF are significant in SEAS during the positive IOD years 1994 and 1997. During negative IOD years latent heat loss is more when compared to positive IOD years. During positive IOD years the heat gain is high in SEAS when compared to negative IOD years. SSHA is the very important parameter to explain the phenomenon like upwelling and downwelling. Summer monsoon seasons of the negative IOD years are recorded with a low SSH than positive IOD years. During the negative IOD years there are significant changes in winter season in terms of coastally trapped wave propagation, when compared to the positive IOD years. Similar pattern is also observed in the case of D20. As compared to the positive IOD years, the negative IOD years showed an uplift of D20 along the west coast of India especially during summer monsoon and fall. This indicates the upsloping of the upwelling mode Kelvin wave. But in December these isotherms deepened and confined to the coast in negative IOD years. During positive IOD years there is no considerable variability in D20.

In positive IOD years, the equatorial current during summer monsoon is towards west. But in SEAS the zonal current is towards east with very less intensity. In negative IOD years these currents are very strong and are towards east. For spring season, the geostrophic current pattern is almost similar for positive and negative IOD years. During summer monsoon, the currents are towards south along west coast of India. During fall season, the coastal waters of west coast of India showed a current pattern towards north in positive IOD years and towards south in negative IOD years. In winter, during negative IOD years there was a strong geostrophic current flowing towards north which was very much confined to the coast. This phenomenon is not identified during positive IOD years.

Another important factor which has reflective impacts on the fisheries is coastal upwelling. The upwelling intensity in positive IOD years is less when compared to the negative IOD years. The immediate biological response of the coastal upwelling is the primary production and along the SEAS, the most productive season is the summer monsoon. During the strong positive IOD year 1997-1998 associated with strong El Niño, the chlorophyll *a* concentration of EAS is found to be less. But during 1998-1999 which was a negative IOD year with strong La Niña the chlorophyll *a* concentration was very high.

During 1991-1999 when the IOD events were frequent, the El Niño - monsoon relationship was weak. But for 2000-2008, there was a high negative correlation between rainfall and Nino 3.4 index. The El Niño-monsoon relation was very strong for 2000-2008 when IOD events were less frequent. La Niña-monsoon relationship during 2000-2008 is strong compared to that of 1991-1999. In the entire study period, the heavy rainfall occurred during the positive IOD events.

When considering the Oil sardine landings of southwest coast of India as a whole, it can be seen that the landings follow a long term variation throughout the study period and the trend shows a linear increase after the 1994 positive IOD year. The positive IOD year 1994 is noted as the lowest fishery year among the two decades. But mackerel landings show a different pattern from the oil sardine landings. The mackerel landings do not show any long term trend, but it keeps seasonality throughout the study period. Along the southwest coast of India oil sardine landings have a long term variation and the mackerel landings follow a seasonal variation.

ARIMA (2,2,1) model has been used to predict the landings of oil sardine. Mackerel did not show any pattern and so the analysis with ARIMA model seems to be difficult in the case of mackerel. The relationship between the landings of oil sardine and mackerel has also been studied. It suggests that the oil sardine and mackerel has a significant negative correlation with 95% confidence level during the study period. Moreover, during the end of the period of study the landings of oil sardine and mackerel show the same trend.

6.1 Concluding Remarks

During the positive IOD years, the oil sardine landings showed drastic changes compared to normal years. The increase in the magnitude of positive DMI shows a decrease in oil sardine landings for southwest coast of India. The landings exhibited a negative correlation with SSH and SMR and a positive correlation with SST, SSS and UI. Fishes are highly migratory with respect to the deepening and shoaling of MLD. The MLD deepening in winter associated with positive IOD years can be considered as one of the reasons for the decrease in oil sardine landings. During the positive IOD years the coastal waters of southwest coast of India showed less upwelling intensity during summer monsoon months as compared to the other years. The intensive rainfall associated with the positive IOD years affect the oil sardine fishery to its larval stage. The low primary production in this area during the positive IOD years inversely affected the fish population in that region. SST and SSS also showed a direct relationship with the oil sardine fishery. The increase in the magnitude of negative DMI showed an increase in oil sardine landings. In negative IOD years, during the fall and winter monsoon months, there was a lowering of SSH and cause shoaling of MLD. During the summer monsoon months of negative IOD years the upwelling intensity is more and caused maximum primary production. These conditions favored a good oil sardine fishery during these years.

From the analysis, it can be seen that SST, SSS and UI showed positive correlation with oil sardine landings and negative correlation with SSH and SMR. SSH showed a maximum correlation (R = -0.765) with oil sardine fishery. The mackerel landings and the environmental parameters do not show any significant relation.

SSH plays a major role in the variations of annual landings of oil sardine along the southwest coast of India. The other parameters such as UI, SMR and SSS also showed variable roles in the variations in annual oil sardine landings. So it is concluded that these environmental parameters stated above, be well accepted for the prediction of oil sardine fishery. In contrary, this prediction method is not applicable to mackerel fishery.

6.2 Limitations of this study

The relevant data on the larval stage of the fishes in the study area is generally lacking. Availability of the data would be served better purpose to reach a concrete conclusion on the impacts of the physical factors on the different life stages of the fishes. The length-weight frequency data on fishes are also not accessible to explain in detail the impact of the climatic variations on size structure of fishes. Another important lacking factor is the availability of sufficient data on migration patterns of different species of the fishes as this could easily establish the link between the fisheries to prevailing ocean currents for this area.

6.3 Scope for future work

1. The effect of advective fluxes which supports the horizontal migration of the different species is an area worth attending.
2. The study can be extended further by considering more species of pelagic fishes and links could be established not only with the physical factors, but also with the chemical and biological factors prevailing over the area of interest.

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