Studies on eggs and larvae of Oil Sardine, Indian Mackerel and Anchovy in the South Eastern Arabian Sea Upwelling System

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Studies on eggs and larvae of Oil Sardine, Indian Mackerel and Anchovy in the South Eastern Arabian Sea Upwelling System

Ph. D. Thesis in Marine Biology

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Front Cover Illustration

Sardinella longiceps larvae, eggs and yolk sac stage collected onboard FORV Sagar Sampada from the study area

CERTIFICATE

This is to certify that the thesis entitled "**Studies on eggs and larvae of Oil Sardine, Indian Mackerel and Anchovy in the South Eastern Arabian Sea Upwelling System**" is an authentic record of the research work carried out by Ms. Sree Renjima G (Reg. No.: 3593), under my scientific supervision and guidance at the Centre for Marine Living Resources & Ecology (CMLRE), Kochi, in partial fulfilment of the requirements for award of the degree of Doctor of Philosophy of the Cochin University of Science & Technology and that no part thereof has been presented before for the award of any other degree, diploma or associateship in any University. Further certified that all relevant corrections and modifications suggested during the pre-synopsis seminar and recommended by the Doctoral Committee have been incorporated in the thesis.

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DECLARATION

I hereby declare that the thesis entitled "**Studies on eggs and larvae of Oil Sardine, Indian Mackerel and Anchovy in the South Eastern Arabian Sea Upwelling System**" is an authentic record of research work conducted by me under the supervision of Dr. V. N. Sanjeevan, Former Director, Centre for Marine Living Resources & Ecology (CMLRE), Kochi and no part of it has been presented for any other degree or diploma in any University.

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Dedication

To My family

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LIST OF ACRONYMS & ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
ANOVA	Analysis of Variance
APO	Apochromatic
ASHSW	Arabian Sea High Saline Waters
AWS	Automated Weather Station
BD	Body Depth
CMLRE	Centre for Marine Living Resources and Ecology
CTD	Conductivity-Temperature-Depth
CZ	Central Zone
DOD	Department of Ocean Development
EBUS	Eastern Boundary Upwelling System
ED	Eye Diameter
EEZ	Exclusive Economic Zone
FAO	Food and Agriculture Organisation
FIM	Fall Inter Monsoon
FORV SS	Fishery Oceanographic Research vessel *Sagar Sampada*
HL	Head Length
ICES	International Council for the Exploration of SEAS
IIOE	International Indian Ocean Expedition
IRAWS	Incident Remote Automated Weather System
LJL	Lower Jaw Length
MLD	Mixed Layer Depth
MoES	Ministry of Earth Sciences
MPN	Multiple Plankton Net
MR-LR	Marine Research Living Resources
NIO	National Institute of Oceanography
NIOA	North Indian Ocean Atlas

NOAA	National Oceanic and Atmospheric Administration
NRL	Naval Research Laboratory
NZ	North Zone
OEW	Optimum Environmental Window
PCA	Principle Component Analysis
PRIMER Research	Plymouth Routines in Multivariate Ecological
SDO	Surface Dissolved Oxygen
SEAS	South Eastern Arabian Sea
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SIM	Spring Inter Monsoon
SL	Standard Length
SM	Summer Monsoon
SSD	Sea Surface Density
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SZ	South Zone
UNDP	United Nations Development Programme
WICC	West India Coastal Current
WM	Winter Monsoon

Chapter 1

Introduction

Studies on the early life history of marine fishes have progressed greatly from the 20th century with the pioneering works of Sette, Ahlstrom, and others (Lasker, 1987). The ichthyoplankton of a region are indicators of the adult species which constitute the fishery of the area. Fluctuations in fishery recruitment are more often associated with variations in ichthyoplankton survival rates. The relevance of ichthyoplankton studies in explaining the variations in abundance of fish populations is receiving more attention recently. The ichthyoplankton undergo a series of ontogenic changes during their development to adult. Irrespective of the habitat of the adult, many of the demersal and epipelagic fishes have a pelagic larval life. Later, as they become juveniles they settle into their adult habitat. Even the location of the spawning grounds and the nursery grounds were they are nurtured are different. The nursery grounds are favourable feeding grounds to which the eggs from the spawning locations should preferably reach so that better survival rates are ensured. There they develop into post flexion stages and juveniles or till they become self-sufficient in feeding. The early life history of the fishes continues to be studied from different perspectives. Some of them deals with the embryological development, others emphasize on the functional morphology of larvae (Kendall *et.al.,* 1981).

1.1 Eastern Boundary Upwelling Systems (EBUS) and small pelagic fishery

EBUSs are characterised by high biological production generated by the surface pumping of nutrients by coastal upwelling and Ekman transport. Four major eastern boundary upwelling systems of the world are Canary Current, California Current, Benguela Current and Humbolt Current system. About 50% of the world's fish catch comes from upwelling areas which constitute only 0.1% of global oceans (Ryther, 1969). EBUS sustains large populations of small pelagic fishes contributing 20-30% of the worldwide annual fish catches (Cushing, 1969). Several studies have been conducted worldwide in these ecosystems following the recognition of distinct food web attributes and remarkable fish production existing here (Ryther 1969; Chavez and Messie 2009). Clupeoid fishes are small pelagic fishes abundant in the productive coastal upwelling regions of the world. Among clupeoid taxa, anchovies are the most abundant in the world's eastern boundary current regions (Bakun and Parrish 1982). They have short life cycle which help the fish stocks to regenerate faster. The recruitment of the small pelagic fishes, undergo wide interannual fluctuations due to instability of the environment, predator abundance and fishing pressure (Freon *et al.,* 2005; Brochier *et al.,* 2009). Thus clupeoid recruitment variations are translated rapidly into their population size which makes their fishery difficult to manage (Cole and Mcglade, 1998).

According to Carr, 2001, since anchovies and sardines are mediated by short food chains (Ryther, 1969), their production is higher in the upwelling regions, but their response to environmental variations is significant and need to be explored more. Anchovy and sardine may

compete for same resources (Wang, 1997). Alternating dominance in catches of two clupeoid taxa sardines and anchovies, are seemingly dominated by long term environmental variations which give rise to regimes (Lluch-Belda *et al.,* 1989). Cury and Shannon (2004) describes regime shifts as sudden shifts in structure and functioning of a marine ecosystem which affects several living components and results in an alternate state. The regime shifts of sardines and anchovies in the Pacific Ocean is associated with multidecadal variability in SST, equatorial currents and atmospheric CO_2 (Chavez *et al.,* 2003). Climate-related regime shifts in Pacific salmon was reported by Irvine and Fukuwaka (2011).

Previous studies generalize that pelagic fishes spawn in regions of favourable food resources and near-shore retention areas to minimise offshore transport to unfavourable areas for feeding and survival (Parrish *et al.,* 1981; Roy *et al.,* 1992). According to Bakun and Parrish (1982), the three environmental processes which regulate the reproductive success of pelagic fishes are turbulent mixing which disturbs the food strata of first feeding larvae, offshore transport from favourable productive habitat resulting in the loss of eggs and larvae and upwelling intensity which regulate the productivity of the system. Cury and Roy (1989) developed a conceptual model (Optimal Environmental Window) describing the relationship between recruitment success and environmental limiting factors. Its major elements included wind stress and associated micro turbulence. They explained that the fish reproductive strategies changes in weak, moderate and strong upwelling areas. Fish recruitment can either be positively correlated or negatively correlated with upwelling intensity. Low wind speed leads to low upwelling intensity and thereby low productivity and fish abundance. At high wind speed, the productivity

drops due to offshore transport and mismatch of larvae and prey (Cushing, 1969). In optimal environmental window concept, the fish production is high at intermediate upwelling favourable winds (Chavez and Messie, 2009). Recent studies by Bakun (1996) on the environmental factors that affect fish reproduction shows the involvement of three major processes that delivers favourable habitat for survival of fish eggs and larvae. They are enrichment process caused by upwelling and mixing, concentration process caused by frontal zones and convergent zones and finally retention process that maintains the planktonic eggs and larvae at favourable nursery grounds which increases the survival rate of larvae and there by the recruitment success. Govoni and Grimes (1992) observed the surface aggregation of fish larvae by the hydrodynamic convergence within the Mississippi River plume front and concluded that frontal convergence was a localized complex mechanism that accumulates the larval fishes. Fish larvae have poorly developed locomotary organs and they possess less swimming ability. Transport of fish larvae can be elucidated with the knowledge on the hydrodynamics of the region. George (2011), made an attempt to develop a numerical model on the transport of fish larvae from the spawning sites in the coastal waters.

1.2 South Eastern Arabian Sea as an EBUS

Arabian Sea is characterized by two dominant seasons, due to varying atmospheric forcing as a result of monsoon wind reversal, categorized as, the Summer Monsoon (SM) from June to end September and the Winter Monsoon (WM) from November to end February interspaced by the Fall Inter Monsoon (FIM) in October and the Spring Inter Monsoon (SIM) from March to end May. The two major ocean processes that contribute to the productivity of Eastern Arabian Sea

(EAS) are upwelling along the south-west coast during SM and convective mixing along the north-west coast during the WM (Madhupratap *et al.,* 2001). The seasonal upwelling prevailing during the south west monsoon (Banse, 1959) bring cold, nutrient rich, dense subsurface water into the euphotic zone (Sastry and D'Souza, 1972). This rich supply of nutrients to the euphotic zone increases biological activity and makes Arabian Sea one of the most productive regions. In the north-eastern parts of the Arabian Sea the production is enhanced by the advection of the nutrients from the Somali upwelling (Prasannakumar *et al.*, 2001) and the open ocean upwelling as a result of the strong wind stress curl associated with the monsoon jet or the Somali/Findlater jet (Prasannakumar and Prasad 1999). Shetye *et al.,* 1990 observed that the circulation off EAS during SM, though weak is dynamically similar to that of world's major wind driven eastern boundary currents. The major forcing mechanisms that induce upwelling along the South Eastern Arabian Sea (SEAS) are the monsoon winds blowing from south west and the north and the remote forcing from the Bay of Bengal (Smitha e*t al.*, 2008). The coastal upwelling provides increased nutrient supply to the euphotic zone and enhances biological production along SEAS (Madhupratap *et al.,* 1990, Gardner *et al*., 1999; Prasannakumar *et al*., 2001; Wiggert *et al*., 2005; Habeebrehman *et al*., 2008). This nutrient enrichment associated with coastal upwelling along SEAS during SM causes a general increase in phytoplankton blooms and zooplankton abundance (Madhupratap and Haridas, 1990, Madhupratap *et al.,* 1990, Habeebrehman *et al*., 2008, Jyothibabu *et al.,* 2008, 2010, Ashadevi *et al.,* 2010). Raj and Ramamritham, (1981) observed that zooplankton bio volume in SEAS was high during monsoon and post monsoon seasons. They studied the inter-relationship between hydrographic features and

plankton biomass along the south west coast of India from Kanyakumari to Mumbai which revealed that the plankton biomass is directly related to the intensity of upwelling along the west coast. George,1989 observed that the abundance of fish eggs and larvae of major pelagic fishes are high during the SM period along SEAS and concluded that the Kerala coast acts as the main breeding site of small pelagic fishes.

1.3 Small Pelagic Fishery of SEAS.

The annual average contribution of pelagic fish to the total marine fish production of India during the years 2009 to 2015 is 55%. (CMFRI Annual Reports, 2010-2016) The south west coast comprising the States of Kerala, Karnataka and Goa contributes the major proportion pelagic fish catches. Oil sardines, anchovies and mackerels dominate the small pelagic fishery of SEAS, an Eastern Boundary Upwelling System (EBUS). Pelagic fisheries is mainly contributed by 7 groups viz, oil sardines, lesser sardines, anchovies, Bombay duck, ribbonfishes, carangids and Indian mackerel (Pillai, 2006). Oil sardines, anchovies and mackerels together contribute 49 % of the total marine fish landings from SEAS. Among these fishes, oil sardine is the most abundant contributing 33.32% of the total landings of SEAS. Indian mackerel, *Rastrelliger kanagurta,* belonging to Scombrid family forms another important pelagic fishery (12.14%) along the south west coast especially Kerala and Karnataka. *Stolephorus sp*. contributes 3.64% of the total south west sector landings. Among the *Stolephorus sp., Stolephorus devisi* is the dominant species along the Kerala coast. Wide inter annual as well as decadal scale oscillations are observed in the catches of these species. Attempts to explain their interannual variations through conventional stock assessment techniques (Z=F+M) have not been successful. This is because recruitments in these fishes are

not fully dependent on stock size, but are rather governed by natural mortality (M) especially during the ontogenic stages. Ashokan *et al.,* 2009 opined that climate related variations in sea surface temperature (SST) have mediated the northward extension of distribution ranges of oil sardine and mackerel populations.

1.4 Ichthyoplankton studies: Historical Account

Early life history studies of fishes have interested the ichthyologists since the days of Aristotle. The discovery of free floating planktonic eggs of Atlantic cod by the Norwegian Research Fellow in Fisheries, Sars (1876) was one of the pioneering studies that initiated the larval systematics (Hempel 1979, Ahlstrom and Moser, 1981, Lalithambika Devi, 2010). Modern ichthyoplankton research can probably be traced back to the 1880s when a unique monitoring program was initiated along the Norwegian Skagerrak coast (study on cod). A rich history of ichthyoplankton studies exists in the western North Atlantic region which includes a wealth of published records and pioneering research partly because of the relevance of ichthyoplankton studies in supporting the fishery management of that area. Some of the pioneering expeditions along both sides of North Atlantic and Mediterranean that yielded knowledge about the early life history stages include U.S. Fish Commission Expeditions of Albatross (1883-1887) covering the western North Atlantic, Danish Oceanographic Expeditions of Thor and others (1905–1912) covering the Mediterranean and North Atlantic region, Dana II Expeditions covering the North Atlantic, Caribbean, Gulf of Mexico and Panama Bay (1928–1930) sponsored by Carlsberg Foundation.

The Canadian Fisheries Expedition (1914–1915) under the leadership of Dr. J. Hjort studied the distribution and varied abundance of fish larvae, as well as eggs of cod, haddock, flatfishes and other species in addition to thorough investigation on distribution, migration and breeding of Canadian Herring in the Atlantic coastal waters of Canada. According to Kendall and Matarese (1994), although ichthyoplankton studies of most of the species of some regions of the world can now be identified; there are many gaps in our knowledge that can be filled only with continuous systematic and traditional morphological research as well as application of biochemical, genetic and rearing techniques. Early life history studies were also initiated in Japan with ichthyoplankton surveys beginning in 1938 (Binu, 2003).

With the latter half of the 20th century research which were till then limited to commercially important food fishes expanded further as the fishery biologists realised the application of ichthyoplankton studies as an indirect tool to evaluate the fishery potential of an area. E. H. Ahlstrom played a major role in expanding the early developmental studies of fishes over geographical and international fronts and in establishing its importance in the assessment of fish populations. He built up a team of young taxonomists researching over the fisheries of the California Current (Blaxter, 1984) and was the first to determine fish population using this technique. In recent years, studies of early life history of fishes have been widely used to resolve the central problems of fishery dynamics, management and culture (Lasker, 1987). Literatures on larval taxonomy describing the larvae of specific geographic regions rather than systematic groups are more useful in the identification of ichthyoplankton (Kendall and Matarese, 1994). Some of the earlier examples of such publications

are Agassiz (1882), Ehrenbaum (1905, 1909), and D'Ancona *et a1.,* (1931-56).

Leis (2015) reviewed the progress in taxonomy and systematics of larvae of Indo Pacific fishes. According to Leis, since nineteen eighties there has been a major progress in the Indo-Pacific fish larval taxonomy with the pioneering works of Ahlstrom during early eighties. A large number of identification guides and publications in traditional journals have been instrumental in the recent progress of icthyoplanktonology in the Indo-Pacific. Recently published guides with descriptions and illustrations of fish and larvae of specific regions around the world are Fish eggs and larvae from the Java Sea (Delsman 1972), Northeast Atlantic (Russell 1976), North West Atlantic (Fahay, 1983), Indo-Pacific Coral reef Fishes (Leis and Rennis, 1983), Moser, *et al.*, 1984, Ontogeny and Systematics of fishes, Western North Oceanic larvae (Ozawa, 1986), Japanese waters larval taxonomy (Okiyama, 1988) Indo-Pacific Shore Fishes (Leis and Trnski, 1989), California Larval Current taxonomy (Moser, 1996), Larvae of Temperate Australian fishes (Neira *et al.*, 1998), Indo-Pacific Coastal Fishes (Leis and Carson-Ewart, 2004), Early stages of Atlantic fishes for Western Central North Atlantic (Richards, 2006) and Eggs and Larvae of North Sea Fishes (Munk and Neilsen 2007). Recently, Lalithambika Devi (2010) described about 24 species of Bothid larvae from the Indian Ocean, Gulf of Thailand and South China Sea in the Monograph on Bothid Larvae (Pleuronectiformes- Pisces) published under the Marine Living Resources Program of the Centre for Marine Living Resources & Ecology (CMLRE).

1.5 Ichthyoplankton studies of the Southwest coast of India

Studies on fish eggs and larvae were pioneered in India by Madras Presidency Fisheries Department. Information on the developmental studies of the early stages of the fishes in the Indian waters is scarce. Some of the earlier ichthyoplankton surveys in the southwest coast of India include Dana Expedition around the world (1928-30), Indo Norwegian Project in co-operation with Central Marine Fisheries Research Institute, which started at 1953, International Indian Ocean Expedition covering the Indian Ocean and the adjacent seas (1960-64), and UNDP/ FAO Pelagic Fishery Project, Cochin (1971-79). Recent systematic larval surveys in the Indian EEZ were undertaken by the multidisciplinary programme on Marine Research – Living Resources (MR-LR) of the Ministry of Earth Sciences, implemented by CMLRE. Many descriptions on developmental stages of Indo - Pacific larval fish particularly marine taxa have come out from these surveys. Descriptions and illustrations by Indian authors, Jones (1958a, 1959a&b, 1960a, b&c, 1961a&b, 1962 a&b) and Bensam (1965; 1966a&b; 1967a&b; 1969, 1973, 1981, 1990) provide basic information on the ichthyolarvae from Indian waters. According to Leis (2015), most of the early publications, before eighties on descriptions of Indo-Pacific larval fishes were that of Japanese and Indian works only. These works provided a vague idea on many of the economically important fish stocks breeding in Indian waters and also revealed that during summer monsoon period the southwest coast of India serve as the major spawning and nursery ground of majority of the coastal pelagic fishes. Studies on maturity stages also indicated that the main breeding season was summer monsoon. The peak spawning in the study area was reported during the southwest monsoon with a secondary peak during the northeast monsoon for some species (George, 1989).

Some of the earlier contributions to the taxonomic studies of ichthyoplankton in the south west coast of India include descriptions on the larval and post larval stages of twenty three fishes off Trivandrum coast (Gopinath, 1946). Nair (1952) described the life history of *Kowala coval* from Calicut. Chacko and Mathew, (1955 & 1956) described the eggs and early larvae of *Decapterus russelli, Caranx crumenophthalmus, C. djeddeba, C. kalla* and *Sardinella aleblla* from south west coast. Balakrishnan (1957) made a brief note on the eggs and larvae of *Rastrelliger kanagurta* from the coastal waters of Vizhinjam. Nair (1960) reported *Sardinella longiceps* larvae from Calicut with its maximum abundance from June to August. Larvae of *Cynoglossus semifasciatus, Arnoglossus tapeinosoma, Bothus ocellatus, Laeops guntheri, Solea ovata, Cynoglossus monopus and Bregmaceros sp.* from Kerala coast was described by Balakrishnan (1961&1963). Jones and Kumaran, (1962) reported the occurrence of post larval stages of *Myripristis murdjan* and *Holocentrus sp*. from the surface plankton collections of Lakshadweep waters. Jones and Kumaran (1963) described the geographical and seasonal distribution of tuna larva in the Indian Ocean based on the collections made by Dana-Oceanographic Expedition (1928-30). The authors distinguished 5 species of Tuna larvae from these collections. They were *Katsuwonus pelamis, Neothunnus macropterus, Euthynnus affinis, Auxis thazard and Auxis thynnoides.*

The planktonic eggs and early larval stages of *Cynoglossus semifaciatus* from the Kannur, SEAS waters were described by Bensam (1965). The illustrations and descriptions of planktonic eggs and early larval stages of *Sardinella jussieu* and Muraenid eel from the near shore waters off Kannur, South west coast of India were given *by* Bensam (1966a & b) from Kannur waters. The embryonic and early developmental stages of *Opisthopterus tardoore,* post larval stages of

Anodontostoma chacunda and *Kowala coval* from Kannur waters were illustrated by Bensam 1967 a&b and 1969. Bennet (1967) studied the seasonal abundance of small sized juveniles of *Rastrelliger kanagurta* from Vizhinjam waters. Descriptions of larval stages of *Pseudorhombus elevatus* along the south west coast of India was given by Lalithambika Devi (1969). Balakrishnan and Rao (1971) reported the post larval and juvenile stages of *Rastrelliger kanagurta* from the waters of Vizhinjam and Kannur. Balakrishnan and Devi (1974) reported the developmental stages of flat fishes, larvae of *Solea heinii, Cynoglossus punticeps, C. brevis, C. cynoglossus* and *C. lida* from Cochin backwaters (tropical estuary). Silas (1974) reported the occurrence of *Rastrelliger kanagurta* larvae from the coastal waters of south west coast in the month of May. Lazarus (1976 and 1985) reported the occurrence of *Sardinella sirm* and *Sardinella longiceps* larvae from Vizhinjam. Kathirvel and Selvaraj (1980) recorded the juveniles of rock cod, *Epinephelus tauvina* from the Cochin backwaters during February to June and described about the morphological variations between juveniles and adults. They also explained the food and feeding habits of juveniles. Peter (1977 and 1982) studied the distribution of tuna larvae in Arabian Sea and a few fish larvae of the Arabian Sea and Bay of Bengal. George (1988) studied the relative abundance and quantitative variations in eggs and larvae of 11 families in the nearshore waters of Vizhinjam including the eggs and larvae of *Sardinella sp* and *Anchoviella sp* and the larvae of *Rastrelliger kanagurta*. Eggs and early developmental stages of Ophichthyid and Muraenid Eels were recorded by George (1988) from the near shore waters off Vizhinjam during January to March. As part of the assessment of the Pelagic Fish resources of the area extending from Ratnagiri to Tuticorin, systematic ichthyoplankton surveys were carried out by UNDP/FAO, Pelagic Fishery Project, Cochin (1971 – 1979) over

the shelf and adjacent waters along the south west coast of India. This survey indicated that all the major pelagic fishes spawned along the south west coast of India during the summer monsoon. Based on this survey, George (1989) gave distribution of *Sardinella longiceps* eggs and larvae, whitebait larvae, mackerel larvae, scombroid larvae, tuna larvae, carangid larvae and larvae of lantern fishes and light fishes. The carangid larvae of *Alepes kalla* and *Alectis ciliaris* of the southwest coast was described by Premalatha (1986 and 1991). Dileep (1989), studied on the larvae of a few demersal fishes from the south west coast of India. Binu (2003) studied the fish larvae of the Arabian Sea with special reference to clupeiformes. Vijay Anand *et al.,* 2005, studied the juveniles on sea grass beds of Kavarathi atoll, Lakshadweep, India. He observed that the juveniles of Acanthuridae and Labridae were most abundant on sea grass beds. The monograph on larvae of flat fishes by Lalithambika Devi (2010), also included SEAS. Early developmental stages, larval growth rates, distribution and abundance of eggs and larvae of Indian mackerel along SEAS were described by Sree Renjima *et.al.,* 2017.

1.6 Relevance of the study

Present assessments of spawning season of fishes are based mostly on gonadal maturation studies on commercial catches. The present study is undertaken with a view to obtain more detailed and finer information on spawning grounds, spawning seasons, spawning intensity and larval distribution of commercially important coastal pelagic species within the South East Arabian Sea (SEAS) upwelling system. Systematic collection of fish larvae in the study area was undertaken to explain the spawning process, transport of eggs and larvae and correlate inter-annual variations in abundance to the prevailing environmental conditions. By correlating

the abundance and distribution of larval stages with environmental parameters, the present study aim to explain the role of environmental factors in the early developmental stages of fish which will help to elucidate the recruitment anomalies that are common in these fishes.

The purpose of the present research work is to document the spatio-temporal variations in the distribution and abundance of small pelagic fish in the upwelling system of SEAS and to evaluate the role of environmental and biological factors in influencing such variations.

1.7 Objectives of the study

- To update and strengthen existing knowledge on the distribution, abundance and taxonomy of Oil sardine, Indian mackerel and anchovy larvae in the SEAS upwelling system.
- To delineate possible spawning grounds and spawning periods
- To correlate fish larval abundance with environmental variables

1.8 Outline of Thesis

The thesis is organised into six chapters, as given below.

Chapter 1:

This chapter gives a general introduction to the topic and the study area. An overview of the small pelagic fisheries of SEAS is given. Previous studies on the early developmental stages of Oil sardine, Indian mackerel and anchovies along SEAS are detailed. The chapter ends with the relevance of the study and listing of the objectives of the study.

Chapter 2:

This chapter provides a detailed picture of the study area with its oceanographic features and geological locations. The sampling methodology used for the collection of ichthyoplankton and hydrographical data are described. Methods adopted in analysis of samples and data are explained.

Chapter 3:

This chapter deals with the morphological features and identification characters of eggs and early larval stages of Oil Sardine, Indian Mackerel and Anchovies.

Chapter 4:

This chapter describes the distribution and abundance of eggs and larvae of Oil Sardine, Indian Mackerel and Anchovies along the SEAS during different phases of SM.

Chapter 5:

In this chapter, hydrographic features of the study area during different phases of SM are described. The spatial and temporal distribution of larval abundance is correlated with the environmental parameters.

Chapter 6:

This chapter summarizes the major findings and conclusions of the study.

References: are listed in bibliography section.
Appendices: Published papers

Chapter 2

Study Area, Sampling Design and Analysis

2.1 *Study Area*

The Eastern Arabian Sea (EAS) encompass two distinct ecosystems namely the North Eastern Arabian Sea (NEAS) roughly occupying the area north of 15^0 N and the South Eastern Arabian Sea (SEAS) occupying the area south of 15^0N. The present study area is restricted to the part of SEAS adjoining the Indian continent (South west coast of India) which is an Eastern Boundary Upwelling System (EBUS). The study area is characterized by two dominant seasons, the Summer Monsoon (SM) from June to end September and the Winter Monsoon (WM) from November to end February interspaced by the Fall Inter Monsoon (FIM) in October and the Spring Inter Monsoon (SIM) from March to end May. Seasonal changes in the hydrodynamics of SEAS are forced by the South-westerlies during SM and the North-easterlies during WM as well as by the Upwelling (SM)/ Downwelling (WM) modes of the coastally trapped Kelvin waves and its offshore propagating Rossby waves (Mc Creary and Chao, 1985; Shetye *et al.,* 1990; Shankar *et al.,* 2002, Gopalakrishna *et al.*, 2008 and Smitha *et al.,* 2008).

In the present study, SEAS is divided into three distinct zones namely the South Zone (SZ), Central Zone (CZ) and North Zone (NZ)

on the basis of geological, physical and chemical attributes. Geo-morphologically the South zone (Cape to Kollam; 7°N – 9°N) is not oriented parallel to the coast (Fig.1.) and experience moderate to intense upwelling from as early as April/May under the influence of strong SM winds that flow tangential to the coast (Bakun *et al.,* 1998). The influence of offshore propagating Rossby waves on offshore Ekman transport is negligible and upwelling is forced purely by the wind stress (Smitha *et al.,* 2008). Unlike the CZ and NZ which experience hypoxic to suboxic conditions during SM and FM, the dissolved oxygen (DO) levels in the water column of SZ including the bottom waters (DO > 0.65 ml/ L) are moderately high during SM and throughout all other seasons. Hypoxic/ suboxic conditions are not prevalent. This zone experiences the intrusion and spread of the low saline oligotrophic waters from Bay of Bengal all over its surface during WM and early SIM seasons. The surface waters are therefore strongly stratified and warm much faster than the Arabian Sea waters leading to the formation of the so called "warm pool" with SSTs above 30^0C (Shankar and Shetye, 1997; Vinayachandran *et al.,* 2007; Sabu and Ravichandran, 2011). The oligotrophic conditions during the SIM season promote the build-up of Particulate Organic Carbon (POC) in the water column and the dominance of a microbial food web.

The central zone (Kollam to Calicut; 9^0N to 11.5^0N) is characterized by moderate coastal upwelling during SM starting roughly from the first week of June. Offshore Ekman transport is quite strong in this zone due to the drag effect of the offshore radiating Rossby waves. Productive waters extend up to 200km off the coast which disperses the plankton far and wide. The unique feature of this zone is the formation of mud banks at several locations along its coastal belt starting from June and extending up to August/September. High primary productivity and

large scale export flux of organic matter especially during October (FIM) leads to severe hypoxic/ suboxic conditions in the water column and bottom waters (DO <0.20 ml/ L). Warm pool is located offshore.

Along the north zone (Calicut to Goa; 11.5^0N to 15^0N) coastal upwelling is active from mid of June and the offshore extent of Ekman transported waters progressively decreases towards northern latitudes due to strong cross shore winds that push the dense Arabian Sea High Saline Waters (ASHSW) coastward. This way the high biological production associated with SM are retained close to the coast. Warm pool is restricted to offshore areas and export flux of organic matter to deeper waters is high during FIM. Water column is hypoxic/ suboxic during SM.

2.2 Sampling Design

Samples for the present study were collected through cruises onboard Fishery Oceanographic Research Vessel *Sagar Sampada* (FORV-SS) (Fig 2.2) carried out under the Marine Living Resources Programme implemented by Centre for Marine Living Resources and Ecology (CMLRE), Ministry of Earth Sciences (MoES). These ichthyolarval survey's were undertaken as part of the projects, *Survey and Assessment of fish eggs and larvae along the Indian EEZ* and *Monitoring and Modelling of Marine Ecosystems* under the MLR programme of CMLRE.

The study area extends along the south west coast of India (Kerala – Goa sector) from 7.00°N to 15.2°N Latitude and 73.71° to 77.64°E Longitude. Stations were located along 12 transects namely Cape- T_1 (8°N), Trivandrum-T_2 (8.5° N), Kollam – T_3 (9°N), Alleppey –T_4 (9.5°N), Kochi –T_5 (10°N), Valappad –T_6 (10.5°N), Calicut – T_7 (11.2°N), Kannur – T_8 (12°N), Mangalore – T_9 (13°N), Bhatkal – T_{10} (13.8°N), Karwar – T_{11}

(14.7°N) and Goa – T_{12} (15.2°N). Horizontal collections of ichthyoplankton samples were taken from stations representing 30m, 50m, 100m, 200m, 500m and 1000m isobaths. (Fig 2.1, Table 2.1).

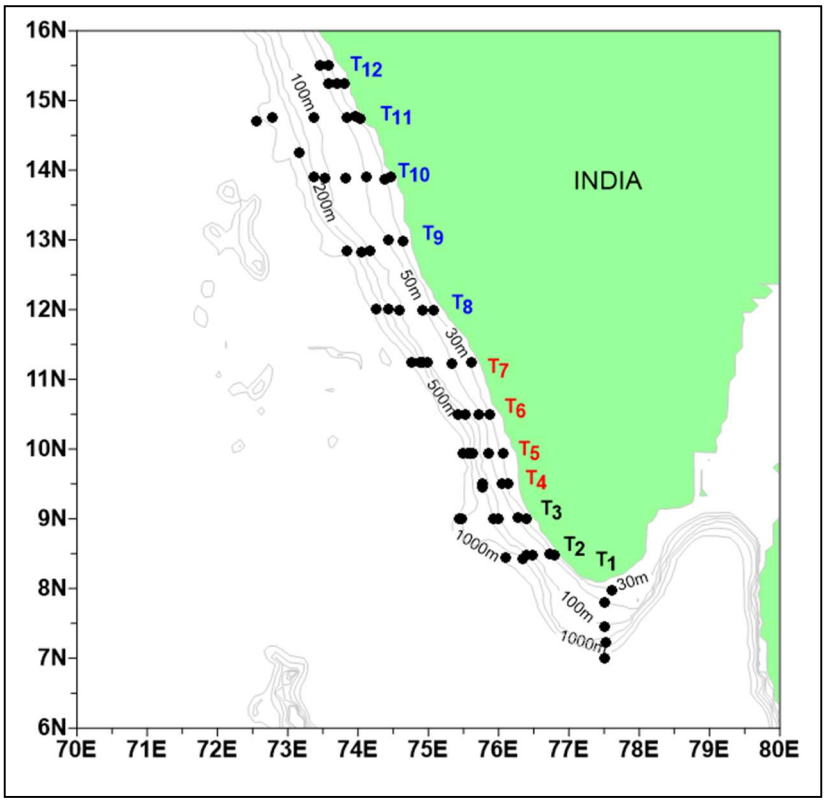


Figure 2.1 Map showing study area and sampling sites along the transects off Cape (T_1), Trivandrum (T_2), Kollam (T_3), Alleppey (T_4), Kochi (T_5), Valappad (T_6), Calicut (T_7), Kannur (T_8), Mangalore (T_9), Bhatkal (T_{10}), Karwar (T_{11}) and Goa (T_{12}). Transects depicted in black denotes south zone, red denotes central zone and blue denotes north zone.

Fig.2.2. Sampling vessel - FORV *Sagar Sampada*

Fig. 2.3. Sampling gear- Hydro Bios Bongo Net

Ichthyoplankton surveys were undertaken on board the Fishery Oceanographic Research Vessel Sagar Sampada (FORV-SS) during the SM upwelling seasons of 2009, 2010, 2013 and 2015. For data analysis and interpretation SM was divided into 3 phases namely phase 1 (from mid-May to mid-June), phase-2 (from mid-June to mid-July) and phase-3 (from mid-July onwards to September end). A total of 234 ichthyoplankton samples were collected from Bongo operations. 10 cruises were conducted during different phases of SM onboard FORV-SS. In 2009, collections were made during the phase1of SM (29 May 2009 to 14 Jun 2009), phase 3 of SM (August, 04 Aug 2009 to 20 Aug 2009) and late phase 3 of SM (18 Sep 2009 to 01 Oct 2009). Seven transects from Cape to Mangalore was covered during these cruises. In 2010, survey was conducted during phase 1 of SM (07 Jun 2010 to 14 Jun 2010) at 2 transects, Cape and Trivandrum. Survey during phase 2 of SM was also conducted at 5 transects from Kollam to Mangalore. In 2013, phase 3 SM (15 Jul 2013 to 14 Aug 2013) collections were taken from all the 12 transects between Cape & Goa. During 2015, samples were collected from 5 transects during phase 1 SM (22 May 2015 to 03 Jun 2015) from Cape to Mangalore and 6 transects during phase 3 SM from Cape to Goa.

Details of sampling period during different phases of SM are given in Table 2.2.

Surface ichthyoplankton collections were carried out by the towing of a 300 microns mesh, Hydro Bios Bongo twin net in a horizontal fashion at surface for 10 minutes with a constant ship speed of 2 knots. A digital flow meter was positioned at the mouth of one of the twin nets to monitor the amount of water filtered. A flow-meter has a propeller which is rotated by the flow of water. The net to which flow-meter was attached was assumed as Bongo net A. A Mutiple Plankton Net (MPN) of Hydro Bios was used to collect mesozooplankton samples from mixed layer. It has a mouth area of 0.25m^2 and mesh size 200 microns and a stainless steel frame attached with 5 net bags which can be controlled from deck unit.

Along with the collection of samples, observations were also made on physicochemical parameters (temperature, dissolved oxygen, salinity, density) from each station using the on-board Sea Bird 911 plus Conductivity, Temperature and Depth sensor (CTD) fitted with 12 liter Niskin bottles. Estimation of Chlorophyll-a was done spectrophotometrically using Perkin Elmer U-V Visible Spectrophotometer following 90% acetone extraction method (Parsons *et al.,* 1984). Meteorological observations on wind speed, wind direction, humidity, air temperature, atmospheric pressure etc. were recorded in 15minutes interval along the track using the IRAWS on-board. Additional oceanographic / meteorological data to support the study were obtained from FORV Data Centre and/or derived from North Indian Ocean Atlas (NIOA) by Chatterjee *et al.,* (2012). Continuous profiling of currents was done up to 500m in 4m/8m bin using the RDI hull mounted broadband (76.5 KHz) Acoustic Doppler Current Profiler

(ADCP). Surface geostrophic currents were estimated using Sea surface height values (JASON-1) and climatological mean dynamic height, processed by the NRL site at the Stennis Space Center and retrieved from NOAA coast watch portal.

Wind induced turbulent mixing was calculated as the third power of wind speed.

The magnitude of Ekman drift is computed as (Pond and Pickard, 1983, Shankar *et al.,* 2002).

$$VE = \frac{\tau}{\rho\,(A\,|f|])^{1/2'}}$$

where τ ıs the magnitude of the wind stress, A is the vertical eddy diffusivity and f is the magnitude of the Coriolis parameter.

2.3 Quantitative analysis and identification of ichthyoplankton

The present study deals with the quantitative and qualitative analysis of ichthyoplankton. Soon after the collection, bongo-samples were filtered through a net with mesh size similar to that of collection net and drained onto a blotting paper. The filtered zooplankon was then transferred in to a measuring cylinder with known volume of preservative (4% buffered formalin in filtered sea water) and the volume displaced by zooplankton was recorded. After the biomass estimation as displacement volume ($ml.m^{-3}$), the mesozooplankton samples were labelled properly

and preserved in 4% formalin (Goswami, 2004) in filtered sea water and brought back to laboratory.

For quantitative analysis of mesozooplankton samples it is necessary to know the exact volume of water filtered by the net. The numerical abundance of ichthyoplankton from the Bongo collections at the time of observation was computed for each station based on calibrated flow meter readings. Larval abundance is represented as ind.$10m^{-2}$ area (Smith and Richardson, 1977) by multiplying the volume of water filtered with the Mixed Layer Depth (MLD). Mesozooplankton samples were sorted to taxonomic groups according to ICES, 1947; Newell and Newell, 1973; Todd and Laverack, 1991 and standardised to ind.$10m^{-2}$.

The volume of the water filtered during the Bongo operation is expressed in cubic metres. It is calculated as follows:-

$$\text{Volume in cubic meters} = \text{Mouth area of the net x Distance (Goswami, 2004)}$$
$$= \pi \times \text{Net radius}^2 \times \text{Distance}$$

$$\text{Distance in meters} = \frac{\text{Difference in flow meter reading x Rotor constant}}{\text{constant}}$$

The biovolume was estimated as follows:-

$$\text{Biovolume} = \frac{\text{Displacement volume (ml)}}{\text{Volume of the water filtered } (m^3)}$$

The biovolume was expressed in ml.m^{-3}

Abundance was estimated as :-

$$\text{Abundance} = \frac{\text{Number of individuals of the particular taxa (No.)}}{\text{Volume of the water filtered } (m^3)}$$

The abundance was expressed as ind. per.m^{-3}

Larval abundance was standardized to ind.$10m^{-2}$ by multiplying the volume of water filtered with the Mixed Layer Depth (MLD) (Smith and Richardson, 1977).

Volume of the water filtered during Multiple Plankton Net operation was calculated as follows:

Volume in cubic meters = (Difference of the depth x Mouth area of the net)

Mesozooplankton abundance was expressed as ind. per.$10m^{-2}$ by multiplying the volume of water filtered with the Mixed Layer Depth (MLD) .

For the qualitative analysis of fish eggs and larvae, they were sorted out from the entire sample and identified. Individual specimens were examined under 10 to 115 X magnifications using Leica S8 APO trinocular stereomicroscope and Leica MZ 16 stereomicroscope. Photographs as well as measurements were taken under Leica DFC 425 Image viewer. Fish larvae were classified and identified using taxonomic guides on the tropical species viz; Larvae of Indo-Pacific Coastal Fishes (Leis and Carson-Ewart, 2004), Ontogeny and Systematics of fishes (Moser, *et al*., 1984) and other published research papers. Identification of oil sardine (*Sardinella longiceps)* eggs and larvae were carried out following the descriptions of Nair 1960, George 1979, Lazarus 1985, Bensam 1990 and Binu 2003. Eggs and larvae of Indian mackerel (*Rastrelliger kanagurta)* were identified using descriptions and illustrations provided by

Balakrishnan and Rao (1971), Peter (1968 and 1982), Silas (1974) and George (1979). Eggs and larvae of the anchovy *Encrasicholina devisi* were identified following Delsman (1931), Wongratana (1983 & 1987) and Binu (2003). Each larva was assigned to a developmental stage based on the notochord flexion (yolk sac stage, preflexion, flexion, and post flexion stage) following Ahlstrom and Ball, (1954) and Lalithambika Devi, (1986).

The yolk sac stage is the first stage after hatching where an anterio-ventrally placed ellipsoid yolk is present. In the preflexion stage, the notochord is straight and the caudal elements are not present. The larvae attains flexion stage, when the notochord slightly starts to bend upwards and the caudal fin elements are present below the notochord but they are not yet complete. During the post flexion stage, the bending of the notochord and the formation of the caudal rays are complete. Schematic representation of developmental stages of fish larvae are illustrated in Fig 2.4

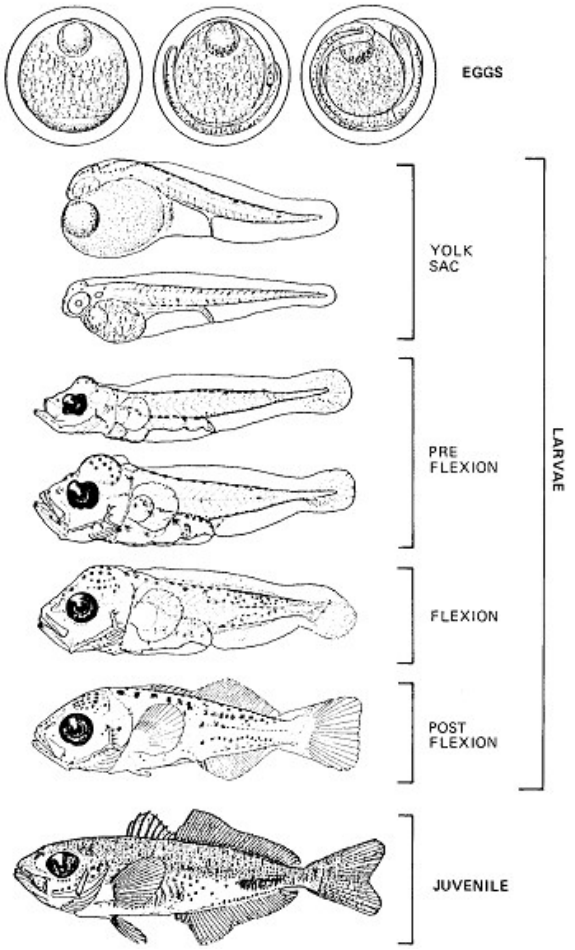


Fig. 2.4 Schematic representation of developmental stages of fish larvae (Ahlstrom and Ball 1954).

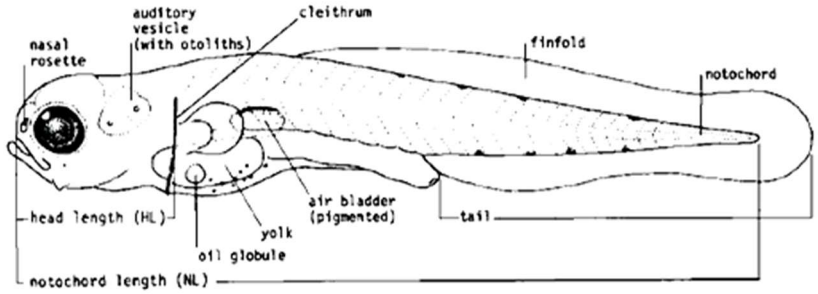


Fig. 2.5 Schematic representation of preflexion larvae (Fahay, 1983)

2.4 Larval morphometric analysis

Morphometric characters like; size and shape of the body, body proportions, length and form of alimentary canal, nature of larval pigmentation, origin and position of fins were the main characters taken into account to identify the larvae. Variable morphometric characters such as Lower Jaw length (LJL), Head Length (HL), Body Depth (BD), Eye Diameter (ED) and Standard Length (SL) were measured using Leica DFC 425 Image viewer attached to S8APO trinocular Stereo zoom microscope. Simple linear regressions of morphometric variables against standard lengths of the larvae were undertaken. The morphometric characters LJL, HL, BD were regressed on standard length of the larvae whereas ED was regressed on the HL.

Terminologies and methods used in morphometric measurements are described here.

Standard Length (SL): Tip of snout to tip of notochord on small larvae, before notochord flexure. Tip of snout to base of hypural plate on larger larvae after notochord flexure.

Head Length (HL): The horizontal distance from the tip of snout to posterior margin of opercular membrane; prior to the development of operculum, measured to the posterior margin of cleithrum.

Body Depth (BD): The vertical distance between body margins through the anterior margin of the pectoral fin base.

Lower Jaw Length (LJL): Tip of the lower jaw to mandible.

Eye Diameter (ED): Horizontal distance between anterior and posterior edges of the fleshy orbit.

The key meristic characters used for identification were fin ray counts and myomere (serial muscle bundles of the body) counts which is divided into preanal and postanal counts.

Preanal Myomeres: Total number of myomeres anterior to the anus.

Postanal Myomeres: Total number of myomeres posterior to the anus.

2.5 Larval growth rate analysis by onboard experimental rearing and field collections

Onboard experimental rearing was conducted to study the developmental stages and to assess the larval growth rates. Eggs were collected through Bongo operations directly from the spawning grounds. Immediately after the collection, they were transferred to Glass tank of 10 L capacity. The tank was filled with ambient sea water of the natural spawning habitat of the fish. Aeration was provided throughout the rearing. The water was filtered daily twice by siphoning out. Water for replacement was collected from the fish breeding site. Subsamples of eggs and larvae were taken at 3-6 hrs interval. They were preserved and labelled in 4% formalin. The standard length of larval samples were measured at shore lab. Daily growth rate of the larvae was established through direct measurements and also by checking the length-frequency mode progression in the SL on time (hrs) plot. Larval growth rates of different spawning stocks were assessed from field data. For this, standard length of the larval specimens from field collections were measured. Daily

increments in standard length and rate of growth of larvae from spawning stocks were estimated separately through eye-fitting the progression in length frequency modes.

2.6 Data Analysis

Statistical softwares, PRIMER 6+ and SPSS 20 were primarily used for statistical analysis. A Principal component analysis (PCA) using PRIMER 6+ was conducted on environmental data to detect trends of variation of environmental parameters across the study area and identify the principal directions in which the data varies (Clarke & Warwick, 1994. To visualize the environmental preferences of eggs and larvae during different phases of SM their abundance was superimposed as bubbles onto the environmental PCA. Graphical representations of study area, spatio-temporal distributions of eggs and larvae were done by SURFER-11. Variations in morphometric data between species were tested using ANOVA by R program.

Table 2.1 Sampling period and phases of SM coverage

Sl No.	Phase	Year	No.of Stations	Sample Collection Time	FORV-SS Cruise
1	Phase 1 – Mid- May to Mid-June	2015	25	Mid May to early June	340
2		2009	39	Late May to mid-June	267
3		2010	12	Early June to mid-June	276
4	Phase 2 – Mid -June to Mid July	2010	20	Mid-June to Early July	276,277
5	Phase 3 – Mid- July and onwards to September end	2013	44	Mid- July to mid-August	316,317
6		2009	29	Early August to Mid August	270
7		2015	30	Early August to Mid August	343
8		2009	35	Mid-September to September end	272

Table 2.2 Location of sampling stations and details of transects and zones.

	Transect	Transect code	Latitude (N)	Longitude (E)	Depth (m)	Phase-1			Phase-2	Phase-3			
						2015	2009	2010	2010	2013	2009	2015	2009
South Zone	Cape	T1	08^0 00.074'N	77^0 38.549'E	30	√	√	√	X	X	√	√	√
	Cape	T1	07^0 48.115'N	77^0 30.519'E	50	√	√	√	X	X	√	√	√
	Cape	T1	07°34.808'N	77°30.081'E	75	X	X	√	X	X	X	X	X
	Cape	T1	07^0 26.275'N	77^0 29.828'E	100	√	√	X	X	X	√	√	√
	Cape	T1	$07^0$13.786'N	77^0 29.466'E	200	√	X	√	X	X	√	√	√
	Cape	T1	07^0 00.346'N	77^0 30.264'E	765	X	X	X	X	X	√	X	X
	Cape	T1	06^0 59.888'N	77^0 31.049'E	1000	X	X	X	X	X	X	X	√
	Cape	T1	07^0 38.745'N	76^0 34.815'E	1450	X	X	X	X	√	X	X	X
	Trivandrum	T2	8^0 30.342'N	76^0 51.002'E	30	√	√	√	X	√	√	√	√
	Trivandrum	T2	8^0 30.040'N	76^0 43.831'E	50	√	√	√	X	√	√	√	√
	Trivandrum	T2	08°16.640'N	76°59.126'E	40	X	X	√	X	X	X	X	X
	Trivandrum	T2	8^0 28.175'N	76^0 29.608'E	100	√	√	√	X	√	√	√	√
	Trivandrum	T2	$08^0$27.902'N	76^0 24.012'E	200	√	√	√	X	√	√	√	√

	Trivandrum	T2	$08^0$27.902'N	76^0 24.012'E	200	√	√	√	X	√	√	√	√
	Trivandrum	T2	8^0 25.991'N	76^0 20.748'E	500	X	√	√	X	X	X	X	X
	Trivandrum	T2	8^0 26.372 'N	76^0 06.035'E	1000	√	√	√	X	X	X	√	√
	Kollam	T3	09^0 00.084'N	76^0 23.524'E	30	X	√	X	√	√	√	X	X
	Kollam	T3	09^0 00.035'N	76^0 17.013'E	50	X	√	X	√	√	√	X	X
	Kollam	T3	08^0 59.897'N	75^0 59.599'E	100	X	√	X	√	X	√	X	X
	Kollam	T3	09^0 00.010'N	75^0 56.851'E	200	X	√	X	X	√	√	X	X
	Kollam	T3	8^0 59.902'N	75^0 28.043'E	500	X	√	X	X	√	X	X	√
	Kollam	T3	09^0 00.350'N	75^0 26.211'E	1000	X	X	X	X	X	X	X	X
Central Zone	Alleppey	T4	09^0 29.904'N	76^0 08.564'E	30	X	X	X	X	√	X	X	X
	Alleppey	T4	09^0 29.754'N	76^0 02.796'E	50	X	X	X	X	√	X	X	X
	Alleppey	T4	09^0 29.960'N	75^0 45.885'E	100	X	X	X	X	√	X	X	X
	Alleppey	T4	09^0 27.150'N	75^0 46.162'E	200	X	X	X	X	√	X	X	X
	Kochi	T5	09^0 56.074'N	76^0 00.413'E	30	√	√	X	√	√	√	√	√
	Kochi	T5	09^0 56.276'N	75^0 50.847'E	50	√	√	X	√	√	√	√	√
	Kochi	T5	09^0 55.926'N	75^0 38.559'E	100	√	√	X	√	√	√	√	√

	Kochi	T5	09^0 56.443'N	75^0 35.667'E	200	√	√	X	√	√	√	√	√
	Kochi	T5	09^0 56.401'N	75^0 33.264'E	500	X	√	X	X	X	X	X	X
	Kochi	T5	9^0 56.477'N	75^0 29.637' E	1000	√	√	X	√	X	X	√	√
	Valappad	T6	10^0 30.045'N	75^0 52.065'E	30	√	√	X	X	√	X	X	X
	Valappad	T6	10^0 29.920'N	75^0 42.693'E	50	X	√	X	X	√	X	X	X
	Valappad	T6	10^0 29.940'N	75^0 31.747'E	100	X	√	X	X	√	X	X	X
	Valappad	T6	10^0 30.203'N	75^0 25.905'E	200	X	√	X	X	√	X	X	X
	Calicut	T7	$11^0$14.917'N	75^0 36.858'E	30	√	√	X	√	√	√	√	√
	Calicut	T7	11^0 13.256'N	75^0 20.30'E	50	√	√	X	√	√	√	√	√
	Calicut	T7	11^0 14.759 'N	74^0 59.348'E	100	√	√	X	√	X	√	√	√
	Calicut	T7	11^0 14.536'N	74^0 55.451'E	200	√	√	X	√	X	√	√	√
	Calicut	T7	11^0 14.959'N	74^0 53.395'E	500	X	√	X	X	X	X	X	X
	Calicut	T7	11^0 14.903'N	74^0 46.229'E	1000	√	√	X	X	X	X	√	√
North Zone	Kannur	T8	11^0 59.471'N	75^0 03.446'E	30	X	√	X	√	X	√	X	√
	Kannur	T8	11^0 59.629'N	74^0 56.361'E	50	X	√	X	√	√	√	X	√
	Kannur	T8	11^0 59.910'N	74^0 35.349'E	100	X	√	X	√	√	√	X	√

	Kannur	T8	12^0 00.043'N	74^0 26.183'E	200	X	√	X	√	X	√	X	√
	Kannur	T8	12^0 00.053'N	74^0 15.868'E	1000	X	X	X	X	√	X	X	√
	Mangalore	T9	12^0 50.754'N	74^0 40.354'E	30	√	√	X	√	√	√	√	√
	Mangalore	T9	12^0 58.500'N	74^0 28.117'E	50	√	√	X	√	X	√	√	√
	Mangalore	T9	13^0 00.288'N	74^0 02.511'E	100	√	√	X	√	√	√	√	√
	Mangalore	T9	12^0 59.534'N	73^0 54.586'E	200	√	√	X	√	√	√	√	√
	Mangalore	T9	12^0 54.191'N	73^0 43.782'E	1000	√	X	X	X	√	X	√	√
	Bhatkal	T10	13^0 53.949'N	74^0 28.058'E	22	X	X	X	X	√	X	X	X
	Bhatkal	T10	13^0 52.51'N	74^0 23.24'E	32	X	X	X	X	√	X	X	X
	Bhatkal	T10	13^0 53.860'N	74^0 7.602'E	52	X	X	X	X	√	X	X	X
	Bhatkal	T10	13^0 52.784'N	73^0 49.836'E	65	X	X	X	X	√	X	X	X
	Bhatkal	T10	13^0 53.397'N	73^0 32.127'E	104	X	X	X	X	√	X	X	X
	Bhatkal	T10	13^0 53.896'N	73^0 22.212'E	203	X	X	X	X	√	X	X	X
	Karwar	T11	14^0 45.080'N	73^0 50.116'E	50	X	X	X	X	√	X	X	X
	Karwar	T11	14^0 14.858'N	73^0 9.493'E	200	X	X	X	X	√	X	X	X
	Karwar	T11	14^0 45.729'N	72^0 46.456'E	1000	X	X	X	X	√	X	X	X

	Goa	T12	15^0 14.892'N	73^0 42.143'E	30	X	X	X	X	√	X	√	X
	Goa	T12	15^0 14.732'N	73^0 48.708'E	23	X	X	X	X	√	X	X	X
	Goa	T12	15^0 29.670'N	73^0 35.234'E	36	X	X	X	X	√	X	X	X
	Goa	T12	15^0 29.742'N	73^0 28.079'E	50	X	X	X	X	√	X	√	X
	Goa	T12	15^0 30.86'N	73^0 044.83'E	100	X	X	X	X	X	X	√	X
	Goa	T12	15^0 29.682'N	72^0 51.162'E	200	X	X	X	X	X	X	√	X
	Goa	T12	15^0 29.564'N	72^0 37.354'E	1000	X	X	X	X	X	X	√	X

Chapter 3

Morphology and larval growth patterns

3.1. *Introduction*

The systematics of fish larvae is as diverse as the systematics of fishes (Moser *et al.*, 1980). Most marine fishes have free floating pelagic eggs which are externally fertilised, regardless of whether they live in pelagic or demersal habitats (Kendall *et al.*, 1981). The pelagic larval stages of marine teleosts are the most significant and crucial phases in their life histories, as larvae of several species coexist and share identical ecological niches. They share common prey and face common predators and abiotic conditions (Moser, 1981). Growth and mortality rates associated with ontogeny are largely dependent on the spawning grounds (Cushing,1975), optimum environmental conditions (Lasker, 1981; Cury & Roy, 1989; Bakun,1996 and Bakun *et al.*,1998), morphological adaptations for swimming, manuovering and ingestion of prey-items (Cushing, 1975, Arthur, 1976, Ostergaard *et al.*, 2005 and Atwood *et al.*, 2010) etc. Fish larvae exhibit wide range of morphological characters that are largely independent of the adult characters (Kendall and Matarese, 1994; Leis, 2015). Larvae of marine teleost's have evolved through morphological adaptations that enable them to successfully occupy a demanding planktonic realm, different from that of adult (Moser, 1981).

According to Leis (2015) the morphological difference between adult and its ontogenic stages are due to the larval features that are only partially developed. However, larvae hold many specializations to support pelagic existence, which are lost on further development to adult. The morphometric and meristic features during ontogeny of marine fishes are species specific. This explains the importance of ichthyoplankton studies and its emergence into a special branch of taxonomy.

Fish larvae are identified using several dynamic characters such as pigmentation, body form, spination, fin development etc. These characters vary rapidly and significantly with growth from larval to preflexion and juvenile stages (Ko *et al.*, 2013) and therefore combinations of these characters and their sequential changes need to be considered for accurate identification of larvae (Powels and Markle, 1984). A developmental series of larvae is a prerequisite for precise identification of the larvae and its developmental stages (Leiby 1981). Such life series can be established either by raising the eggs from known parents or by identifying the specimens from field collections by working out crucial characters backwards from juveniles to early life stages.

Much work have been carried out around the world to elucidate the larval morphology of pelagic species. These include illustrations and descriptions of *Sardinella sp* by Delsman (1926a), Delsman (1933), Conand and Fagetti, (1971), Houde and Fore (1973), Matsura (1975) and Conand (1977). Taxonomic works on eggs and larvae of *Stolephorus sp* include Delsman (1931), John (1951), Miller *et al.*, (1979), Wongratana (1983), Mundy (1990). Eggs and larvae of *Rastrelliger* sp. have been reported by Delsman (1926b; 1931), Matsui (1963; 1970). Rearing techniques have also provided valuable information on early

developmental series of fishes (Lasker, 1987). Some of the earlier rearing experiments on Pacific Sardine were conducted by Fariss (1959), Butler and Mendiola (1985), Kimura and Sakagawa (1972). Jones (2006) reared *Sardinops sagax* eggs to study its early developmental stages. Recently, developmental series of *Stolephorus commersonnii* were illustrated by Gao *et al.,* (2016) based on rearing and molecular techniques. Results of rearing experiments conducted on Pacific mackerel (*Scomber japonicus*) by Hunter and Kimbrell (1980) and Atlantic mackerel (*Scomber scombrus*) by Mendiola *et al.,* (2007) illustrates the early stages of these species. Age and growth of King mackerel (*Scomberomorus cavalla*) and Spanish mackerel (*Scomberomorus maculatus*) larvae were reported by De Vries (1990).

Taxonomic works on oil sardines and anchovy larvae along South Eastern Arabian Sea (SEAS) include illustrated descriptions of eggs and preflexion larvae of oil sardine by Nair (1960), Lazarus (1985), Bensam (1990) and Binu (2003). Spatial and temporal distribution of oil sardine eggs and larvae were reported by George (1979 and 1989) and George (1988). A preliminary note on larval stages of *Stolephorus sp.* was given by Gopinath (1946) from Trivandrum coast. Quantitative measurements of eggs and larvae of *Anchoviella sp*p. collected from Vizhinjam waters were given by George (1988). Occurrence of larvae of *Stolephorus sp.* from SEAS was reported by George (1979, 1989); in the collections of UNDP/FAO pelagic fishery project with taxonomic descriptions. Binu (2003) described few engraulid larvae from SEAS with morphological features and photographs of post flexion stages of *Encrasicholina devisi*, *Stolephorus waitei* and *Stolephorus indicus.*

Earliest reports of eggs of Indian Mackerel (*Rastrelliger kanagurta)* were published by Delsman (1926b), Devanesan and Jones (1940),

Balakrishnan (1957) and Kuthalingam (1956). These were mere reports on occurrences, lacking detailed taxonomic descriptions and illustrations. Taxonomic works on Indian mackerel from SEAS was carried out by Balakrishnan and Rao (1971) with morphological descriptions and illustrations of post larvae and early juveniles. The smallest specimen described in their study measured 8.7mm. Peter (1968, 1982) described eggs and 3 early larval stages of Indian mackerel collected from Persian Gulf, Red Sea and Bay of Bengal during the International Indian Ocean Expedition (1960-65). Descriptions and features of larval development were also illustrated by Silas (1974) based on larval specimens in the size range 1.73mm to 8.6mm. Occurrence of mackerel larvae from SEAS were also reported by George (1988), George (1989) and Binu (2003).

3.2. *Methodology*

Fish eggs and larvae were collected through random sampling from field stations. Standard procedures and techniques as explained in Chapter-2, were followed to study larval morphology and growth patterns in oil-sardine, Indian mackerel and anchovies from the upwelling system of SEAS. Larval morphology and growth rates derived through this study were compared with actual observations obtained through limited rearing experiments carried out using the aquarium facilities on board FORV- SS. Eggs and larvae of *Sardinella longiceps*, *Rastrelliger kanagurta* and *Encrasicholina devisi* were identified with the aid of published research papers as described in Chapter 2. Morphological features of egg, yolk-sac stage, pre flexion, flexion and post flexion stages of sardine, anchovy and mackerel larvae as observed under stereo zoom microscope are described. For morphometric analysis, 5 variable morphometric characters from a

total of 137 larval specimens of varying sizes were utilized as described in Chapter 2. Larval growth rates of oil-sardines and Indian mackerels derived from rearing experiments are also explained. The detailed methodology of field collection, on board rearing and morphometric definitions and terminologies are described in Chapter 2.

3.3. *Results*

3.3.1. *Larval characters of Clupeiformes*

Clupeiformes are small pelagic, schooling fishes most often found in upwelling areas. Order Clupeiformes is composed of commercially important groups such as sardines, sardinellas, herrings, shads (Family: Clupeidae) and anchovies (Family: Engraulidae). Larvae of Clupeiformes are characterised by an elongate and slender body. They are planktivorous and have straight long gut with serially arranged melanophores. The head is devoid of spines. Body is lightly pigmented and characteristic cross hatched muscle fibres are present.

3.3.2. *Larval characters of Clupeidae*

Larvae of Clupeidae are characterized by a transparent, slender and elongate body. Myomeres (muscle plates) vary between 40 and 60 in number. Head small to moderate, without spines. Clupeids have a longer gut relative to body length. Melanophores (pigment cells) present along the gut. Some taxa have few melanophores around notochord tip. Dorsal and anal fins are posteriorly located. Dorsal fin develops prior to anal fin. The base of the dorsal fin is always anterior to the anal fin. Anus located far behind. During the transformation stage, anus migrates anteriorly thus

altering the number of preanal and post anal myomere count (Houde *et al.,* 1974). Muscle fibres in a cross-hatched pattern present in most taxa.

3.3.2.1 Eggs and larval stages of *Sardinella longiceps*

a) Egg morphology

Eggs are pelagic, transparent and spherical with an average diameter of 1.17 ± 0.049mm. In the present study, egg diameters ranged from 1.06mm to 1.26mm (N=95). Chorion smooth and unpigmented. Yolk possess polygonal segmentation. A single golden yellow coloured oil globule with a diameter of 0.13mm present. Perivitelline space is wide. The yolk forms 63% of the total egg size. Oil globule present at the tail end of the embryo. In late stages of the egg, prior to hatching, a series of paired melanophores develop on the dorsal side of the embryo. Myomeres also develop on the body. Just before hatching the tail becomes separated from the yolk mass and bends.

b) Yolk sac stage: (2.865mm to 4.3mm SL)

Newly hatched larvae from field collections were approximately 3.3mm in length, whereas newly hatched larvae from rearing experiments ranged between 2.865mm and 4.3mm in length. The larvae were transparent, slender and elongated with an ellipsoid yolk-sac of 0.94mm length on the anterio - ventral part of the body. The head was bending over the ellipsoid yolk. A single golden yellow oil-globule with a diameter of 0.12mm, located ventrally towards the middle part of the yolk. Eyes not pigmented. The alimentary canal is straight, long and with a visible vent. A series of paired melanophores (24) present on the dorsal side of the body. Melanophores were also present on the tip of the notochord. Pectoral bud and caudal rays develop at the 3.43mm SL stage. The larvae

depend exclusively on yolk for feeding. As larval growth progresses, the yolk-sac reduces in size. On reaching 4mm SL, the yolk was almost completely absorbed and the length of the yolk-sac was reduced to 0.71mm. At this stage the mouth starts to form. The larva has 48 myomeres of which 41 are pre anal and 7 are post anal. The yolk sac is completely absorbed within 30-32 hours post hatching.

c) Pre-Flexion stage

Pre-flexion larvae are transparent and elongated in shape, measuring 4.59mm to 5.5mm SL (field collections) and between 4.3mm and 4.6mm SL in the rearing experiments. At 4.3mm larval length, the yolk sac was completely absorbed. Mouth well developed and the larvae depend solely on planktonic food source. The larvae have a total of 47 myomeres of which 39 are preanal and 8 are post anal. This stage of ontogeny is characterized by pigmented eyes, a straight notochord and appearance of flap like dorsal and anal fins. A series of melanophores (20) present on the ventral side of the body, throughout the length of the alimentary canal. The pigments which were on the dorsal side at the yolk sac stage have now migrated to the ventral side of the body. Pigment spots also appear on the base of notochord. Pre-flexion stage extends from 2nd day post hatching to the 4th day.

d) Mid-Flexion stage

Mid-Flexion stage is represented by larvae measuring 5.4mm to 9.79mm in SL. Notochord begins to bend at 5.4mm at caudal region. The larvae are elongated and translucent and characterized by the presence of 47 myomeres of which 39 are pre-anal and 8 are post anal. Teeth absent and the pectoral fins well developed. Dorsal fins well developed with 15-

18 rays and anal fins with 12-14 rays. A series of melanophores (18) present on ventral side of the body. Caudal fin base with 2 pigment spots. A single melanophore present on the neck. Mid-flexion stage extends up to 8 days post hatching.

e) Post Flexion stage

Post flexion larvae are 9.6mm to 15.18mm in SL. Larvae are elongated in shape and opaque. Post-flexion larvae possess 47 myomeres of which 39 are pre-anal and 8 are post-anal. Teeth are absent on both jaws. Notochord bend at 45° angle at the caudal peduncle. Melanophores (18) on the ventral side of the body. 2 pigments on caudal fin base and a single melanophore present on the neck. Dorsal fins well developed with 17-18 rays and anal fins with 13-16 rays. Swim bladder present. The largest specimen in the post-flexion stage obtained in the present study was 15.18mm SL.

The eggs and larval stages of *Sardinella longiceps* are illustrated in Plate 1 &2.

3.3.2.2 Larval growth rates in oil-sardine

Oil sardine eggs collected from spawning grounds were immediately transferred to aquaria tanks filled with oxygenated sea water (aerators) to monitor the development. The eggs hatched within 19 - 22hrs after spawning and entered the yolk sac stage. Growth in length (SL) of the post-hatch oil sardine larvae were measured in two separate rearing experiments conducted during May 2015 (08°30.040'N, 76°43.831'E) and August 2015 (11°55.007'N, 75°07.634'E). Water temperature was maintained at 26°C - 28°C in both experiments. In the rearing tanks, the

larvae lived only for 4 days post hatching during May 2015 and for 3 days post hatching during August 2015. The standard length of each larva was measured at 3-6 hour intervals from preserved sub-samples. Using this, daily growth rate of oil sardine larvae was established through power regression analysis of standard length on time. The daily growth rate for the May batch (Fig 3.1) was found to be 1.12 mmD^{-1} (0.047mm/hr) for the first 3 days post hatching (n=98; R^2 = 0.44). The daily growth rate of larvae reared in August was 1.44 mmD^{-1} for first 2.5 days post hatching. (n=62; R^2 = 0.694) (Fig. 3.2). The growth rates recorded in the rearing experiments represent growth of the larvae during the yolk-sac stage, the stage at which the yolk-sac is completely absorbed and the starting of preflexion stage.

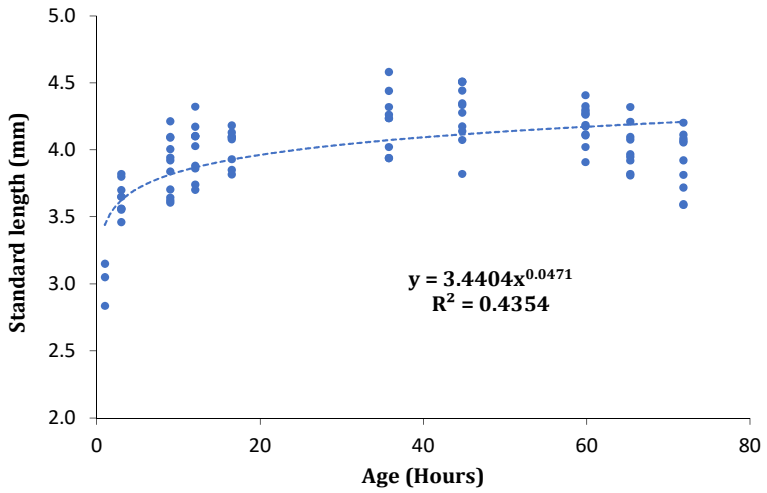


Fig. 3.1. Daily growth rate of *Sardinella longiceps* larvae for first 3 days (May)

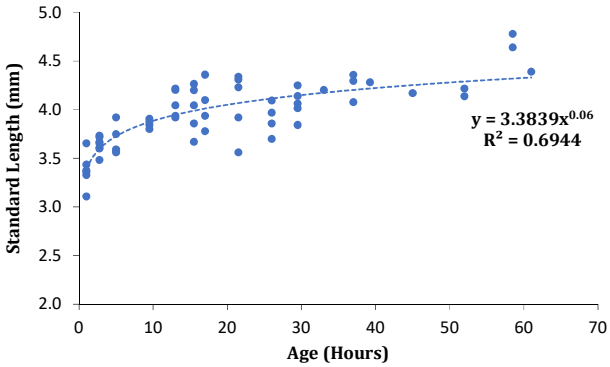


Fig.3.2. Daily growth rate of *Sardinella longiceps* larvae for first 2.5 days (August)

Daily growth increments in length and rate of growth for the subsequent larval stages were estimated separately through eye-fitting the progression in length frequency modes from field data up to the stage the larva reached ~ 15mm in SL. The growth rates of oil sardine larvae for the May-June spawning stock of south zone was 0.955 mmD^{-1} (Fig. 3.3) and for July spawning stock of central zone, the growth rate was estimated to be 0.726 mmD^{-1} (Fig. 3.4). Larvae from May-June spawning stock grew much faster (Y= 0.955X+1.7907) compared to the larvae from July stock (Y=0.726X + 2.6327).

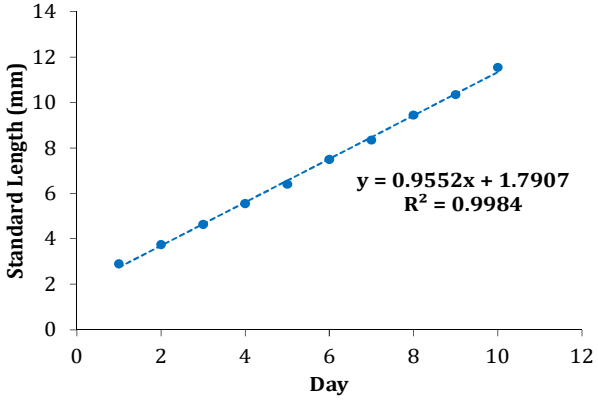


Fig. 3.3 Growth rate of *Sardinella longiceps* larvae of May- June stock

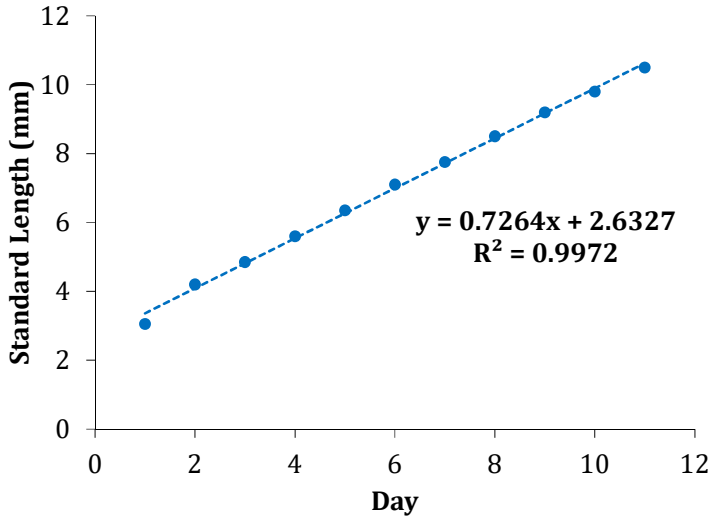


Fig. 3.4 Growth rate of *Sardinella longiceps* larvae of July stock

3.3.2.3 Larval morphometrics : *Sardinella longiceps*

Morphometric comparisons are based on a total of 51 larval specimens of *Sardinella longiceps.* The standard length of *S. longiceps* larvae ranged from 4.05mm to 13.98mm. Morphometric growth patterns in *S.longiceps* were assessed by linear regression of independent variables, the Head Length (HL) (Table 3.1), Body Depth (BD) (Table 3.2) and Lower Jaw Length (LJL) (Table 3.3) on Standard Length (SL) which was taken as the dependent variable. Linear regression of Eye Diameter (ED) (Table 3.4) was done taking HL as the independent variable. The regression coefficients (b) of 0.192X for HL (Fig 3.5), 0.090X for BD (Fig 3.6), 0.085X for LJL (Fig 3.7) and 0.041X for ED (Fig 3.8) implies that growth increments in LJL are much lower in *S. longiceps* compared to BD and HL.

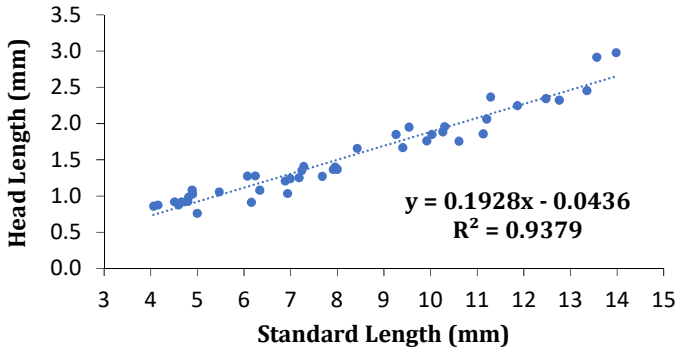


Fig. 3.5. Head length of *Sardinella longiceps* larvae against Standard length

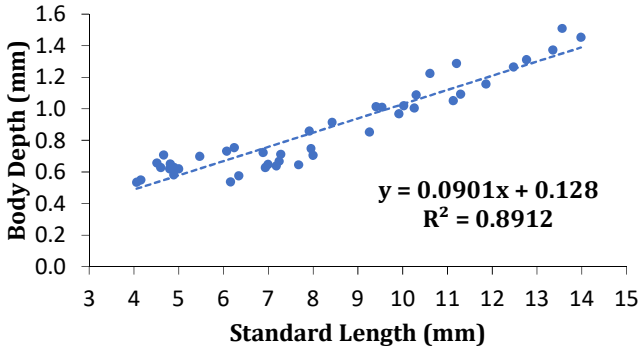


Fig. 3.6. Body depth of *Sardinella longiceps* larvae against Standard length

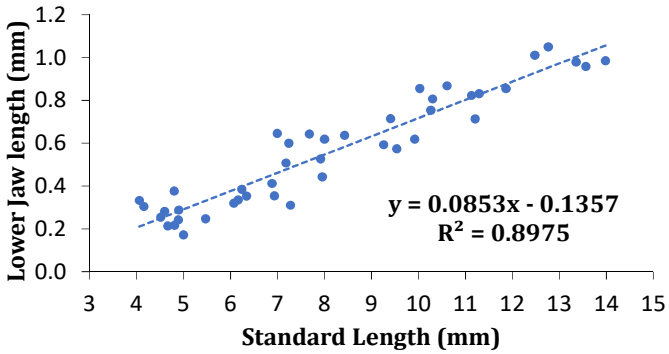


Fig. 3.7. Lower Jaw length of *Sardinella longiceps* larvae against Standard length

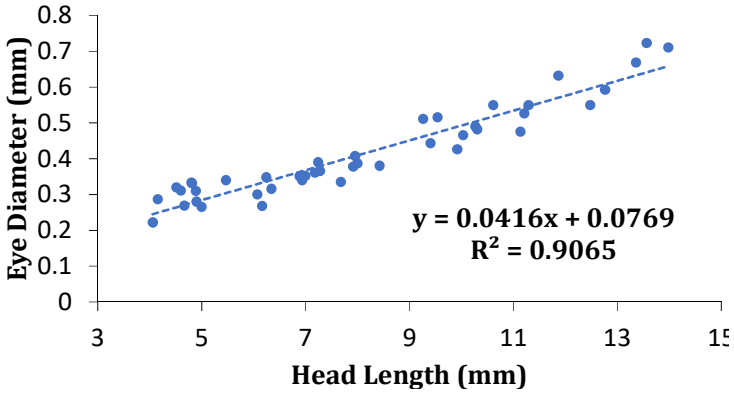


Fig. 3.8. Eye Diameter of *Sardinella longiceps* larvae against Head length

3.3.3 Larval characters of Engraulidae

The body of Engraulid larvae is slender, elongate and cylindrical. Head slightly depressed and devoid of spines. Gut long and striated, striation prominent in hind gut. Engraulids have shorter gut compared to clupeids. The presence of a conspicuous inflated gas bladder on midgut is a characteristic feature of engraulids. Cross hatched pattern of muscle fibres are present. Dorsal and anal fins posteriorly located. Anal fin originates below the second half of dorsal fin, the degree of overlap varying among genera. Body lightly pigmented particularly on the gut.

3.3.3.1 Eggs and larval stages of *Encrasicholina devisi*

a) Egg morphology

Eggs are pelagic, oblong/ellipsoidal without knob at one end. The average length of egg was 1.05mm (N=45) and width was 0.534mm. Egg lengths range between 1.00mm to 1.06mm and widths between 0.520mm to 0.555mm. Oil globule absent. Chorion smooth and transparent. Perivitelline space narrow. Irregularly segmented yolk.

b) Yolk sac stage

The newly hatched larva from the field collections measure 2.72 mm SL. A distinct ellipsoidal yolk present at the anterio-ventral side. Body elongate and transparent. Eyes are not pigmented. Length (SL) of larvae during yolk-sac stage range from 2.72 to 3.5mm. At 3.34 mm, the length of the yolk sac is 0.468 mm. The pectoral bud is present at this stage. A series of melanophores (29) are present on the dorsal part of the larvae. A patch of melanophores present on the tip of the notochord. Myomeres were not distinct. Notochord was straight and the alimentary canal elongated.

c) Pre Flexion stage: (3.49mm - 4.8mm)

Preflexion larvae have 42 numbers of myomeres of which 25 are pre-anal and 17 are post anal. Body elongate, slender and transparent. Eye pigmentation well developed. Pectoral bud present. Notochord straight. Dorsal and anal fin not developed and present as flaps. A series of 19 melanophores present along the ventral side of the body throughout the alimentary canal. Preflexion stage is upto 4th day post hatching.

d) Mid Flexion stage: (4.69 mm to 5.80mm)

Total number of myomers remain 42 at this stage also. Pre-anal region possess 25 myomeres and postanal region possess 17 myomeres. Dorsal and anal fins present as flaps and not completely developed. An inflated swim bladder present at the midgut. Pectoral bud developed. At this stage notochord begins to bend. 3 melanophores present on base of caudal fin, 3 pigment spots on the neck and 15-16 pigment spots on the ventral side of the trunk. Mid flexion larvae possess 12-13 dorsal rays and 15-16 anal rays.

e) Post flexion stage: (5.7 mm to 17.13 mm (largest specimen))

Post flexion stage is characterised by the presence of 42 myomeres of which 24 are pre-anal and 18 are post-anal. Swim bladder well developed. Alimentary canal straight. Teeth are absent. Pectoral fins present. Notochord bend at 45° angle at the caudal region. Melanophores (3 nos) present on base of caudal fin. 3 pigment spots present on the neck and 19-20 pigment spots present on the ventral side of the trunk. Dorsal rays number 13 -14 and anal rays – 17-18.

The eggs and larval stages of *Encrasicholina devisi* are illustrated in Plate 1 &3.

3.3.3.2 Larval Growth Rates of *Encrasicholina devisi*

Larval growth rates of *E. devisi* could not be assessed through rearing experiments, as the eggs failed to hatch in the aquarium tanks. However, growth rates derived from mode progression of larval length frequencies were estimated. The rate of growth of larvae hatched in the month of May under natural conditions in the south zone was found to be 0.61 mmD^{-1} (Fig. 3.9) using which SL can be derived from the regression equation $Y=0.609X+2.408$ ($R^2 = 0.988$). Growth rate of larvae hatched during the month of July in the central zone was found to be 0.57 mmD^{-1} (Fig. 3.10) and SL of these larvae could be expressed by the equation $Y= 0.578X +2.816$ with an R^2 of 0.992. Larval growth curves of the two spawning stocks (May & July) did not show significant variations ($P>0.5$).

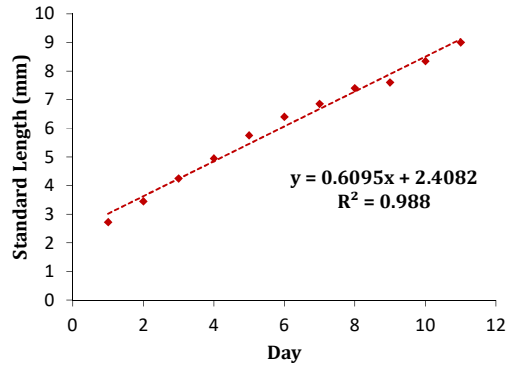


Fig. 3.9. Growth rate of *Encrasicholina devisi* larvae of May- June stock

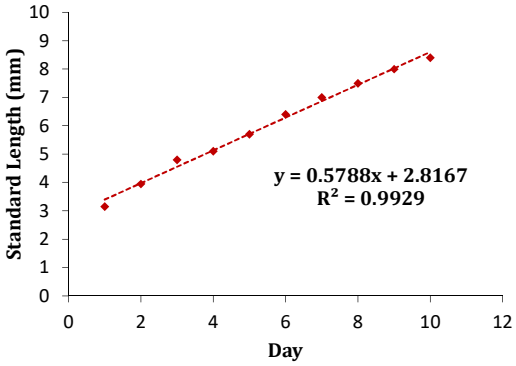


Fig. 3.10. Growth rate of *Encrasicholina devisi* larvae of July stock

3.3.3.3 Larval morphometrics: *Encrasicholina devisi*

Morphometric characters were studied in 37 larval specimens of *Encrasicholina devisi* ranging from 2.72mm to 9.97mm SL. Independent variables such as Head Length (HL) (Table 3.1), Body Depth (BD) (Table 3.2), and Lower Jaw Length (LJL) (Table 3.3) were regressed on Standard Length (SL) to derive morphometric growth equations. Eye Diameter (ED) (Table 3.4) was regressed on HL. The derived regression coefficients (b) for HL (0.213 X), BD (0.089X), LJL (0.084X) and 0.201X for ED (Fig.

3.11 to 3.14) implies that growth increments in HL are much faster in *E.devisi* compared to BD, LJL and ED.

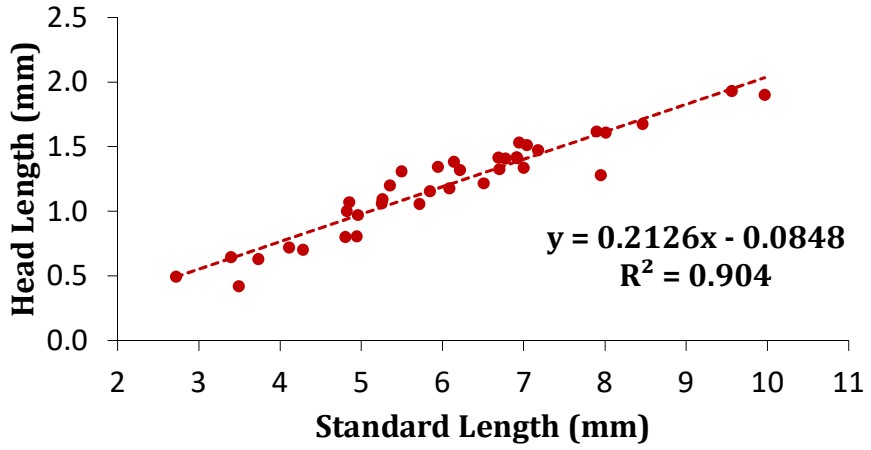


Fig. 3.11. Head Length of *Encrasicholina devisi* larvae against Standard length

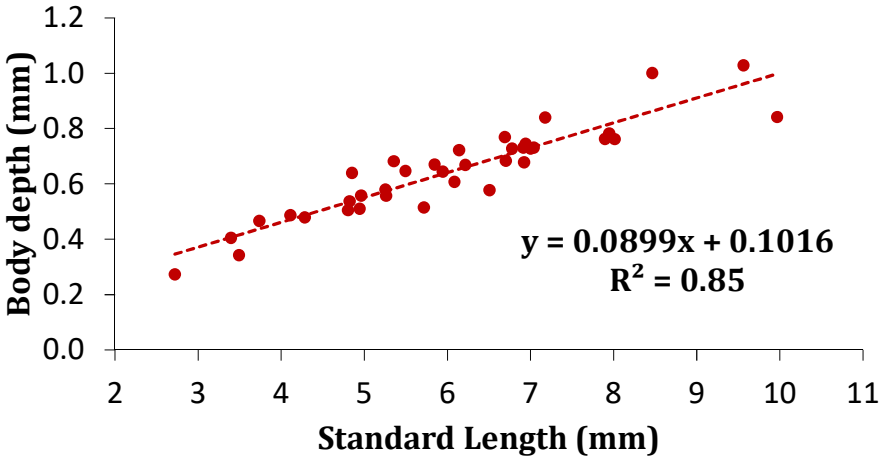


Fig. 3.12. Body depth of *Encrasicholina devisi* larvae against Standard length

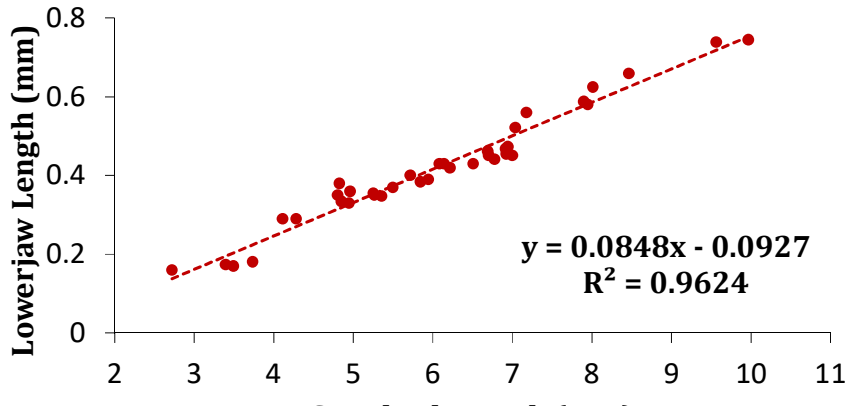


Fig. 3.13. Lower Jaw length of *Encrasicholina devisi* larvae against Standard length

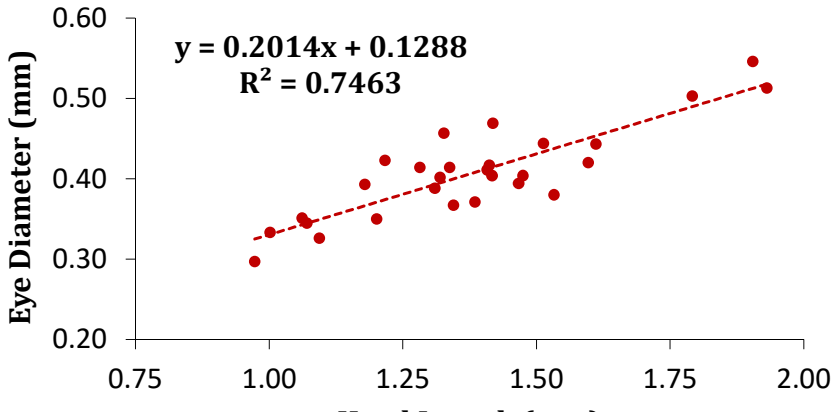


Fig. 3.14. Eye Diameter of *Encrasicholina devisi* larvae against Head length

3.3.4 Larval characters of Perciformes

Perciformes is a highly diverse order represented by mackerels, tunas, seerfishes (Scombridae), carangids (Carangidae), baraccudas (Sphyraenidae), perches (Percidae), gobies (Gobiidae), Swordfishes

(Xiphiidae), ribbonfishes (Trichiuridae) etc. and therefore a generalized description is insufficient to explain the larval characteristics of Perciformes. Larvae show extreme size variations but are usually moderate in shape. Alimentary canal coiled in many of the genera. Many of them have head spination. Presence of spines on fins are common. Adipose fin not present. Body pigmentation present in many groups.

3.3.5 Larval characters of Scombridae

Larvae generally moderate in depth and are laterally compressed. Myomere number varies between 31 and 64. Gut compact, coiled and triangular in shape. Large head and a body deeper at head and trunk regions, than at the caudal end. Eye round and large. Mouth large, jaws equal in most genera, in some the upper jaw projects beyond the lower jaw in post flexion larvae. Most of them have pointed snout. Teeth present on both jaws. Preopercular spines and post temporal spines are present in most genera but they are absent in mackerels. Gas bladder present, but inconspicuous. Dorsal and anal finlets present in some taxa. Relatively wide gap between anus and the anal fin. Pigmentation present on midbrain, gut and trunk in most of the genera.

3.3.5.1 Eggs and larval stages of *Rastrelliger kanagurta*

a) Egg morphology

Eggs are pelagic, spherical and with a smooth chorion. Egg measures 0.91mm to 0.98mm in diameter with an average diameter of 0.96 (N=52). A single large oil globule with a diameter 0.23mm to 0.25mm present. Eggs possess narrow perivitelline space. Pigment spots present on the embryo.

b) Yolk-sac stage: (1.49mm to 2.84mm SL)

The newly hatched larva has a curled shape with a distinct yolk sac on its anterio-ventral side. The larvae possess 24-25 myomeres which are not very distinct. The ventral side of the body has 18 melanophores. Eyes are not pigmented. Notochord straight. Fins are not distinct. Few larvae from field collections measuring above 3 mm SL still retained reduced yolk sac. At 2.84mm, the length of yolk sac was 0.45mm.

c) Pre Flexion stage: (1.8mm and 3.3mm SL)

Body moderately built. Alimentary canal coiled and extend up to 48% SL. Posterior part of gut protrudes out. The larvae are devoid of pre opercular spines. Dorsal and anal rays not distinct, but seen as a continuous fin fold. Of the 30 myomeres present, 7 are pre anal and 23 are post anal. Mouth lacks teeth. The ventral margin of the body has 19 melanophores and dorsal margin is not pigmented. Melanophores absent on occipital region. A single melanophore on urostyle and two pigment spots on the side of gut base.

d) Flexion stage: (2.85mm to 4.85mm in SL)

Alimentary canal coiled, compact and forms 49% of SL. Of the 30 myomeres that are clearly visible, 7 are pre anal and 23 are post anal. The notochord flexion starts from 2.85 mm SL. Rays not distinct and clear. Pelvic fin not developed. Teeth start to appear at 4.1mm SL. A series of melanophores present on the ventral margin of the body (15), lower base of caudal peduncle (2), occipital region (2) and side of gut (3 to 4).

e) Post Flexion stage: (4.6mm to 11.3mm SL)

Larvae (11.3mm) represent the largest specimen in the present study. Body laterally compressed with moderate body depth. Body deeper at the head and gut than at the tail. Gut triangular shaped and coiled. Alimentary canal extends up to 54% of the SL. Teeth present both on the upper and lower jaw. Pre-opercular spines absent. First dorsal with 8 spines and second dorsal with 12 soft rays. 12 anal soft rays present. Dorsal and anal finlets 6 each and 12 -13 caudal rays present. Pelvic fin-buds appear in specimens above 8mm SL. Stellate pigments (13-14) on occipital region. Melanophores on tip of upper jaw (4) cleithral opercular region (4), lower cleithral region (1) and posterior to jaw (1). Pigment spots (4 nos) present on the lower base of caudal fin and 2 on mid of caudal peduncle at the angle of flexion. Dorsal pigmentation develops as the larvae reach post flexion stage. 15 melanophores present on the dorsal fin base from middle of body to caudal peduncle. 3 melanophores present on side of gut. 12 - 13 melanophores on the ventral margin of the body.

The eggs and larval stages of *Rastrelliger kanagurta* is illustrated in Plate 1 &4.

3.3.5.2 Larval growth rates in *Rastrelliger kanagurta*

Newly hatched mackerel larvae (4 numbers) reared in aquarium tanks on-board FORV-SS measured between 1.49mm and 1.78mm SL and survived only for two days. Growth curves fitted on larval frequency modes show significant difference in the growth pattern of larvae from May-June (Fig.3.15.) and July-August (Fig.3.16.) spawning stocks ($p<0.05$). F-test gives a value of 2.775 with P as 0.00076 between the two variables. Larvae from May-June spawning stock grew much faster (Y =

0.339 X + 2.3004) than the larvae from July-August spawners (Y = 0.204 X + 1.7155). On hatching, the larvae from both the spawning stocks were almost of the same length (1.5mm & 1.54mm SL), but after the first week of growth, larvae from the May-June batch reached 4.75mm SL, whereas those from the June-July batch were only 3.13mm SL. At the end of the second, third and fourth week the variations in larval length (SL in mm) were 7.56 & 4.84, 9.55 & 5.98 and 11.3 & 7.2 mm SL respectively.

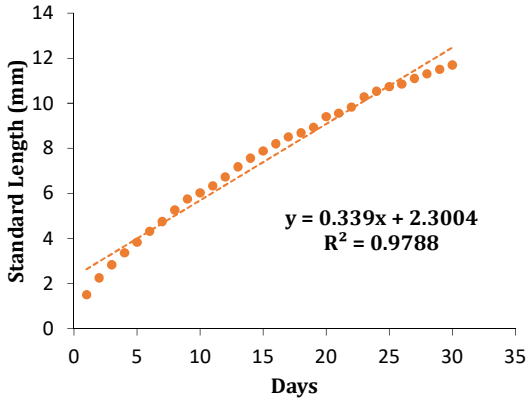


Fig. 3.15. Growth rate of *Rastrelliger kanagurta* larvae of May- June stock

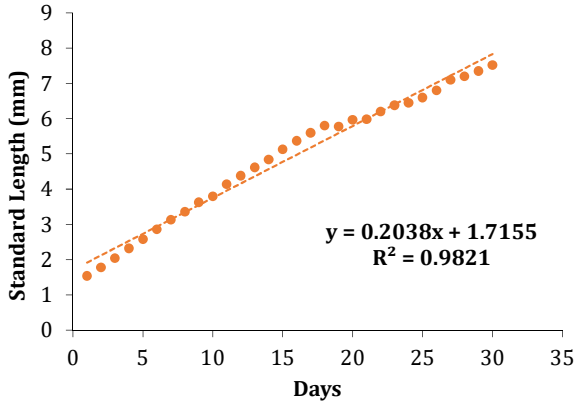


Fig. 3.16. Growth rate of *Rastrelliger kanagurta* larvae of July-August stock

3.3.5.3 Larval Morphometrics: *Rastrelliger kanagurta*

Mackerel specimens (49 larvae) of varying sizes were analysed to explain morphometric characters. The standard length of *R. kanagurta* larvae ranged from 1.75mm to 11.37mm. Mackerel larvae is found to exhibit allometric growth patterns of body parts. The linear regression of independent variables such as the HL (Table 3.1), BD (Table 3.2) and LJL (Table 3.3) on SL (dependent variable) of *R. kanagurta* larvae was studied to represent morphometric growth patterns. The ED was linearly regressed against HL (Table 3.4) which was taken as the dependent variable. The regression coefficients (b) obtained were 0.296 X for HL (Fig 3.17), 0.276X for BD (Fig 3.18), 0.099X for LJL (Fig 3.19) where X represent SL and 0.328X for ED (Fig 3.20) which implies that growth increments in HL are much faster in *R.kanagurta* as compared to BD and LJL.

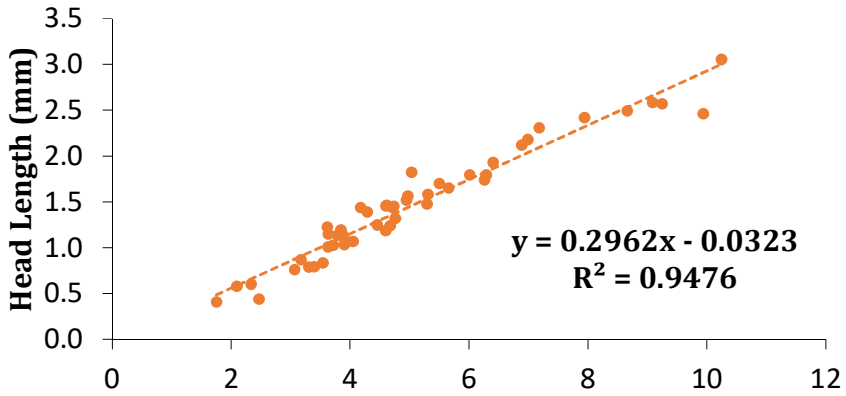


Fig. 3.17. Head length of *Rastrelliger kanagurta* larvae against Standard length

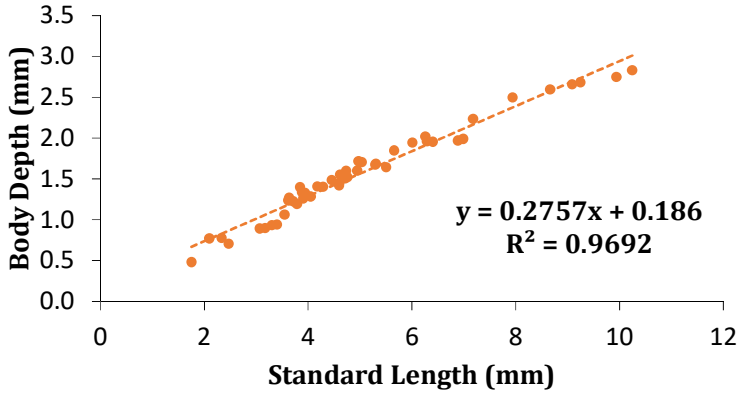


Fig. 3.18. Body depth of *Rastrelliger kanagurta* larvae against Standard length

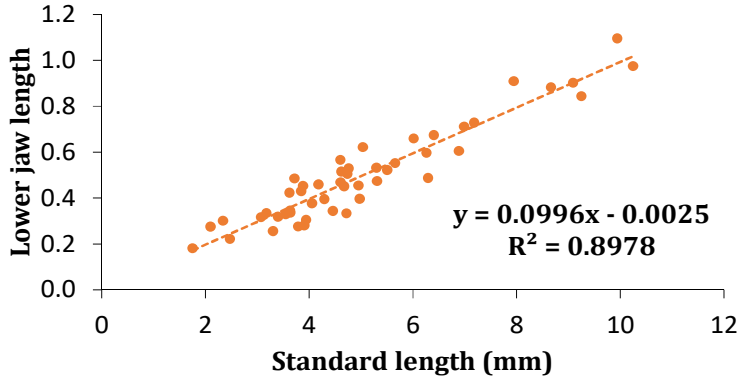


Fig. 3.19. Lower jaw length of *Rastrelliger kanagurta* larvae against Standard length

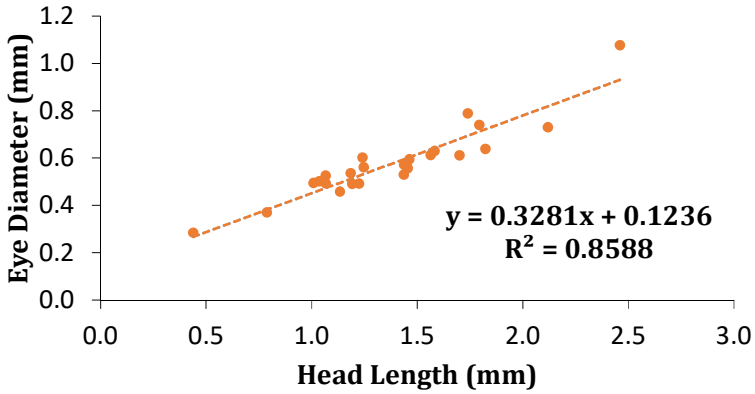


Fig. 3.20. Eye diameter of *Rastrelliger kanagurta* larvae against Head length

3.4. Discussion

a) Eggs

Eggs of oil-sardine and mackerel are spherical in shape, whereas egg of anchovy is ellipsoidal. The 3 species also show marked variations in egg size. Egg size is comparatively large in oil-sardine (average 1.17±0.049mm dia.), followed by anchovy eggs (average 1.05mm in length and 0.534mm width) and mackerel eggs (Average 0.96mm dia.). Largest range in egg size was observed in oil-sardines (1.06mm to 1.26mm dia.), followed by anchovy (1mm to 1.06mm in length and 0.52mm to 0.55mm in width) and mackerel (0.91mm to 0.98mm dia.). This indicates to the possibility that the annual spawning stock of oil-sardines may comprise of multi age-groups, whereas in the other two species, active spawners may belong to only one or two age-group/s. Both oil-sardine and mackerel eggs show a single large oil-globule, whereas in anchovy eggs, oil-globule is absent. Oil-sardine eggs have large perivitelline space, whereas in anchovies and mackerels the perivitelline space is narrow.

Intraspecific variations in egg size and its ecological implications have been reported by Ware (1975). It is known that larger eggs produce larger larvae which have a positive influence on growth and survival (Brooks *et al.,* 1997; Kalmer, 2005). Though wide variations in egg-size were observed in the present study, relationship between egg size and length of newly hatched larvae were not attempted for fear of damaging the eggs while handling.

According to Nair (1960) the oil sardine eggs have a diameter of 1.4mm. George (1979) reported that the eggs ranged from 1.1mm to 1.4mm in size. Lazarus (1985) reported oil sardine planktonic eggs of

2.43mm diameter which is greater than all other observations. In the present study, the eggs measured between 1.06mm to 1.26mm in diameter which is in conformity with George (1979). Sardine eggs possess an ellipsoid yolk with a single oil globule as observed by Nair (1960) and Bensam (1990). Oil sardine eggs collected in the present study were spherical, transparent and with wide perivitelline space which are in conformity with the previous studies (Nair 1960, George 1979, Lazarus 1985, Bensam 1990). The eggs of *E. devisi* from the present study were ellipsoid, without a knob and lacked oil globule which agrees with Delsman (1931), Wongratana (1983 & 1987). Studies on intraovarian eggs of *Stolephorus devisi* by Syda Rao (1969) revealed that the length of the oozing eggs of stage V varies from 1.00mm to 1.3mm. In the present observations the ova diameter ranged from 1.00mm to 1.08mm. The eggs of Indian mackerel are spherical with single oil globule as reported by Delsman (1926b); and Peter (1968). The diameter of the eggs of the Indian mackerel ranged from 0.91 to 0.98 mm in the present observations. Peter (1968) reported that the diameter of mackerel eggs varied from 0.7mm to 0.9mm and Delsman (1926b) observed that the eggs ranged from 0.85mm to 0.95mm in diameter.

Development time of the egg is greatly dependent on temperature and it is species specific (Kendall *et al.*, 1981). High temperature accelerates the development of egg until hatching (Lasker 1964, Blaxter 1981). The length of incubation time of oil sardine eggs at temperature, 26°C to 28°C was recorded as 19-22 hours. According to Lo *et al.,* (1996), at 22°C the length of incubation time of Pacific Sardine eggs was 22 hours.

Newly hatched larvae (yolk-sac stage) of the three species show distinct variations in their body length (SL) and body shapes. Oil-sardine

larvae are slender and elongate and on hatching are 2.86mm in SL, whereas in *E.devisi* though the larvae were slender and elongate in shape, their SL was relatively less (2.72mm). Nair (1960) recorded the length of newly hatched sardine larva as 2.75mm. The body of mackerel larvae are in general broad and curled and their SL on hatching are the lowest among the 3 species (1.49mm). The above observations are in conformity with the views of Brooks *et al.,* (1997) and Kalmer (2005) that larger eggs produce larger larvae, which have a positive influence on larval growth and survival.

b) Larval stages

In the yolk-sac stage, the larvae subsist fully on the yolk. The transition stage from yolk-sac to the first feeding phase (preflexion stage) is a critical period in the life history of the larvae. Among the three species studied, the yolk-sac of oil-sardines was relatively large (0.94mm in length) compared to the yolk-sac of *E.devisi* (0.468mm) and Indian mackerels. The large size of the yolk sac in oil sardines, causes the head and notochord to stretch and bend leading to an overall increase in SL at this stage. According to Matsui (1970), the absorption of yolk sac of *Rastrelliger* larvae takes place at 1.3mm to 1.7mm. Silas (1974) noted that the yolk absorption can be up to about 2mm TL. In the present study it was observed that the complete absorption of yolk took place at 2.8mm SL. Peter (1968) observed 2 stellate pigments on the occipital region of 3.1mm SL mackerel larvae and reported that the larvae lacks teeth at this stage. According to Silas (1974), the teeth appear at 3.38mm. In the present study, appearance of teeth was observed when the larva reached 4 mm standard length.

Gao *et al.,* (2016), observed that in *Stolephorus commersonnii*, the pectoral fin emerges at 12 hours after hatching in the yolk sac stage and the yolk sac is completely absorbed by 72 hours. In the present study, in *Encrasicholina devisi,* the pectoral bud was present at 3.34 mm larvae from the field collections. The yolk sac is absorbed completely by 3.5mm SL stage. According to Gao *et al.,* (2016), the newly hatched larvae of *Stolephorus commersonnii* measures between 1.92mm and 2.08mm. Balakrishnan (1969) observed that the newly hatched larvae of *Thrissocles sp* belonging to Engraulidae family measures 2.1mm in length. In the yolk sac stage, larvae of sardines and anchovies show conspicuous pigmentation on the dorsal side, whereas dorsal pigments are absent in Indian mackerels. However18 melanophores were represented on the ventral margin.

Pre flexion larvae of oil sardine are transparent and measure 4.30mm to 4.60mm in SL. The yolk sac is completely absorbed by the 4.3mm larval stage (30-32 hrs. post hatching). Mouth well developed and the larvae start feeding on planktons. Alimentary canal is long and straight. Anus which was located behind the 41st myomere during yolk sac stage migrate to the 39th myomere with an overall reduction in the SL of the larvae. Melanophores which were on the dorsal side of the alimentary canal during the yolk sac stage (24 pairs) migrated to the ventral side (20 pairs). Similar observations were also made by Nair (1960). After 72 hours, a shrinkage in the length of the larvae was observed. Nair (1960) and Farris (1959) have also reported that a reduction in the length of larvae was observed after the complete absorption of the yolk sac. Pre flexion stage in oil sardine lasted up to 4 days. Mid flexion sardine larvae were translucent and measured between 5.4mm and 9.8mm in SL. Alimentary canal well developed, both upper

and lower jaw without teeth and the anus opens behind the 39th myomere. Of the 21 pigment spots (melanophores) 18 were on the ventral side, 2 were on the caudal fin base and a single pigment spot on the neck. Lazarus (1985), described a 7.64mm larva characterised by 47 myomeres in which the anus was at the 39th myotome and the dorsal fin well in front of the anal fin origin as in the present observations. The mid flexion stage in oil sardine extends up to the 8th day post hatching. Post flexion larvae of oil sardines, anchovy and Indian mackerel were 9.6mm, 5.7mm and 4.6mm respectively at the start of this stage. Well-developed swim bladder was present in anchovies, whereas in the other 2 species the swim bladder was not conspicuous. The upper and lower jaws of both sardines and anchovies lacked teeth even in the post flexion stage, whereas in mackerels teeth were present in both jaws. Well-developed neck pigmentation and presence of 42 myomers in post flexion stages of oil sardine larvae as reported in the present study are consistent with the observations of Binu (2003). According to the present observations Rastrelliger larvae have a total of 30 myomeres and lacks preopercular spine which agrees with the reports of Peter (1968) and Silas (1974).

c) Larval growth rates

Between the species, oil sardine larvae show faster growth rates ($1.12mmD^{-1}$) as compared to *E. devisi* ($0.605mmD^{-1}$) and *R.kanagurta* ($0.339mmD^{-1}$). Within the species, significant variations in growth rates are observed between the larvae from the May-June and July-August spawning stocks of oil sardine and mackerel, whereas in the case of *E.devisi* such variations in larval growth rates are not significant. The observed variations in the growth rates of the first two species are perhaps dependent on the availability of preferred food items in the right size-class (pico and nano

planktons) during the initial phase of summer-monsoon upwelling than at later stages of the season where diatoms dominate the planktons. *E. devisi* is capable of ingesting larger food particles from the early larval stages which perhaps explain their near normal growths both in May and July-August. In the rearing experiments on oil sardines growth rates of larvae from August batch were much higher ($1.44mmD^{-1}$) compared to the May batch ($1.12mmD^{-1}$). This may be due to the fact the annual spawning stock of oil sardine comprises of multi-age groups with the May spawning cohort dominated by the first time spawners (lay smaller sized eggs) whereas higher age groups dominate the latter stages of the peak spawning season (lay comparatively bigger sized eggs). However, in the case of *R.kanagurta* the reverse of this pattern occur with the May-June batch showing faster growth rates ($0.339mmD^{-1}$) as compared to the July-August batch ($0.204mmD^{-1}$). This may be due to the fact that the annual spawning stock of mackerel are composed of only one or two age groups and therefore age dependent variations in egg size are minimum. Nevertheless, mackerels are known to be batch spawners and therefore eggs from the early batches are expected to be comparatively larger than the eggs from subsequent batches.

Studies conducted by Farris (1959) reveal that Pacific sardine (*Sardinops caerulea*) had a growth rate of $0.8mmD^{-1}$ for first 2 days, $0.2mmD^{-1}$ for the next 3 days and $0.1mmD^{-1}$ for the last 2 days. Butler *et al.,* (1985), conducted laboratory rearing on Peruvian sardine (*Sardinops sagax*) and the growth rate was found to be $0.8mmD^{-1}$ at a size of 12.7mm. Average growth rate of sardine larvae was reported as $0.7mmD^{-1}$ by Kimura and Sakagawa (1972) and $0.82mmD^{-1}$ as Jones (2006). In the present study, the growth rate of *S. longiceps* was recorded as $1.12mmD^{-1}$ which is higher than the other observations. The higher growth rate

recorded in the present study may be due to the higher temperature, effective niche partioning and presence of upwelled waters. Study on the growth rate of oil sardines and mackerel larvae shows that the oil sardines have higher growth rates than mackerel. Faster growth rate accelerates metamorphosis, reduces mortality rate during the larval period and thus is indirectly linked to survival (Takasuka *et al.,* 2007). Butler *et al.,* (1985), noted that among clupeoid larvae, sardines have the highest growth rate. According to him faster growth rate in sardine larvae is a feature of seasonally late spawners and it enables them to reach an optimal juvenile size in a seasonal window and attain greater swimming speed. It grows faster than laboratory reared anchovy larvae at similar temperature (Blaxter and Hunter, 1982). Ahlstrom (1966) also noted that sardines dominated at regions where superficially similar sardines and anchovies co-existed.

d) Larval morphometric patterns

Morphological characters are frequently used in fishery biology to study the distinctness and relationships among different taxa (Daud *et al.,* 2005). Morphometric characters describe the aspects of body shape while meristic characters represent the countable structures (Turan, 2004). Variations in the morphometric characters are now considered to be caused both by genetic and environmental factors (Turan 2004; Foote *et al.,* 1989; Robinson and Wilson 1996; Cabral *et al.,* 2003). Most of the marine fishes undergo several changes in their morphological features during the critical period between spawning and recruitment to adult population (Kendall *et al.,* 1981). In the present study, the morphological details of eggs and larvae of oil sardine, Indian mackerel and *E. devisi* are examined.

Morphometric growth patterns in oil sardines, *E.devisi* and Indian mackerel based on the analysis of 139 specimens indicate that growth in these species is allometric. Studies by Ostergaard *et al.,* (2005) & Bachiller and Irigoien (2013) also show that most fish larvae grow in an allometric fashion. It is found that there are significant differences in LJL/SL between species (ANOVA, $F=70.81$, $P<0.001$), HL/SL between species (ANOVA, $F=217.5$, $P<0.001$), BD/SL between species (ANOVA, $F=2105$, $P<0.001$) and ED/HL between species (ANOVA, $F=856.3$, $P<0.001$) (Table 3.5). Pairwise comparisons using Post-hoc Analysis (Tukey-HSD) indicate that there are significant differences in morphometric variables between species (Table.3.6) The difference is very strong between mackerel-sardine ($p=0.0000000$) and mackerel-anchovy ($p=0.0000000$). The difference between anchovy-sardine though statistically significant are not as strong as mackerel-sardine and mackerel-anchovy ($p=0.0079723$).

Lasker (1981) reported that the swimming and maneuvering abilities of fish larvae are dependent on body depth (BD), whereas mouth gape (LJL) determine the maximum size of prey the larvae is able to ingest. The BD to SL is less in oil sardines and anchovies (0.09X and 0.089X) and high (0.276X) in Indian mackerel which implies better swimming and maneuvering capabilities for the first two species, compared to Indian mackerels. Similarly the ratio between LJL & SL gives an indication of the mouth gape of the species and its ability to ingest bigger sized food items. The ratio is highest in mackerels (0.099X) compared to anchovies (0.0848X) and oil sardines (0.0853X). This implies that mackerel larvae can feed on a wide size-range of food items. Arthur (1976) noted that Jack-mackerel can ingest particles 3 times larger in diameter than can sardine larvae of same length.

Results from the present study show that for the first feeding mackerel larvae (3.1mm SL), the lower jaw length and body depth are 0.306mm and 1.041mm respectively while for oil sardine (4.5mm SL.) the values are 0.248mm (LJL) and 0.533mm (BD). In the first feeding anchovy larvae (4.1mm SL) the lower jaw length and BD are 0.255mm and 0.470mm respectively. It is observed that the larvae of mackerel attain a greater body depth and higher lower jaw size than sardine and anchovy throughout the course of larval ontogeny. This enables mackerel larvae to feed on larger prey than similar sized clupeoid larvae; thereby compensating their low swimming and maneuvering abilities, by feeding on a wide size spectrum of food items. Peterson *et al.,* (1984) studied the diet and selective feeding by larvae of Atlantic mackerel *Scomber scombrus* and observed that the first feeding larvae (3.5mm in SL) where phytophagous. The diet of 4.5mm larvae were composed of nauplii and that of larvae > 5mm were composed of copepodites. They observed that the larvae $\geq$ 6.5mm were cannibalistic eating smaller larvae. According to Conway *et al.,* (1999) larvae of *Scomber scombrus* <5mm in length fed on phytoplankton, copepod eggs and copepod nauplii. They also observed piscivorous feeding in larvae in the length range 4mm to 7.9mm. In the present study, the development of teeth of Indian mackerel larvae was observed at 4.1mm which can be related to its piscivorous habits. Morote *et al.,* (2010), studied the larval feeding of sardine and anchovy in the north-west Mediterranean and observed that anchovy and sardine larvae have similar diet composed of phytoplankton, copepod nauplii and post nauplii. But it was observed that anchovy larvae began feeding on prey items >150µm at smaller larval sizes than sardine larvae which continue to feed on smaller sized prey until they reach 10mm SL.

Table 3.1 Morphometric relationship (HLXSL) of larvae

		(HL)		(SL)						
Species	**N**	**Min**	**Max**	**Min**	**Max**	***a***	***b***	**95% Cl-a**	**95 % Cl - b**	**R^2**
S.longiceps	51	0.761	2.978	4.057	13.978	-0.044	0.193	-0.179 – 0.091	0.177 – 0.208	0.94
E.devisi	37	0.421	1.931	2.72	9.966	-0.085	0.213	-0.234 – 0.064	0.189 – 0.236	0.90
R.kanagurta	49	0.406	3.332	1.752	11.373	0.055	0.01	-0.143 – 0.078	0.276 – 0.317	0.95

Table 3.2 Morphometric relationship (BDXSL) of larvae

		(BD)		(SL)						
Species	**N**	**Min**	**Max**	**Min**	**Max**	***a***	***b***	**95% Cl-a**	**95 % Cl - b**	**R2**
S.longiceps	51	0.534	1.51	4.057	13.978	0.128	0.09	0.042 – 0.214	0.080 – 0.100	0.89
E.devisi	37	0.273	1.028	2.72	9.966	0.102	0.09	0.020 – 0.183	0.077 – 0.103	0.85
R.kanagurta	49	0.483	3.251	1.752	11.373	0.186	0.276	0.108 – 0.264	0.261 – 0.290	0.97

Table 3.3 Morphometric relationship (LJLXSL) of larvae

		(LJL)		(SL)						
Species	**N**	**Min**	**Max**	**Min**	**Max**	***a***	***b***	**95% Cl-a**	**95 % Cl - b**	**R2**
S.longiceps	51	0.17 - 1.05		4.057 - 13.978		-0.136	0.085	-0.214 – -0.057	0.076 – 0.094	0.89
E.devisi	37	0.16 – 0.745		2.72 – 9.966		-0.093	0.0847	-0.129 – -0.057	0.079 – 0.090	0.96
R.kanagurta	49	0.174 – 1.362		1.752 – 11.373		-0.002	0.1	-0.056 – 0.051	0.090 – 0.109	0.89

Table 3.4 Morphometric relationship (EDXHL) of larvae

		(ED)		(HL)						
Species	**N**	**Min**	**Max**	**Min**	**Max**	***a***	***b***	**95% Cl-a**	**95 % Cl - b**	**R2**
S.longiceps	48	0.222	0.723	0.761	2.978	0.077	0.042	0.041 – 0.113	0.037 – 0.046	0.91
E.devisi	28	0.297	0.546	0.97	1.93	0.129	0.201	0.063 – 0.195	0.154 – 0.249	0.75
R.kanagurta	25	0.285	1.077	0.439	2.46	0.124	0.328	0.041 – 0.207	0.277 – 0.0386	0.86

SL, Standard length: LJL, Lower jaw length: HL, Head length: BD, Body depth: ED, Eye Diameter: N, Number of samples: *a*, Intercept: *b*, slope: CL, confidence level: R^2, correlation coefficient

Table 3.5 Morphometric growth patterns of larvae between species

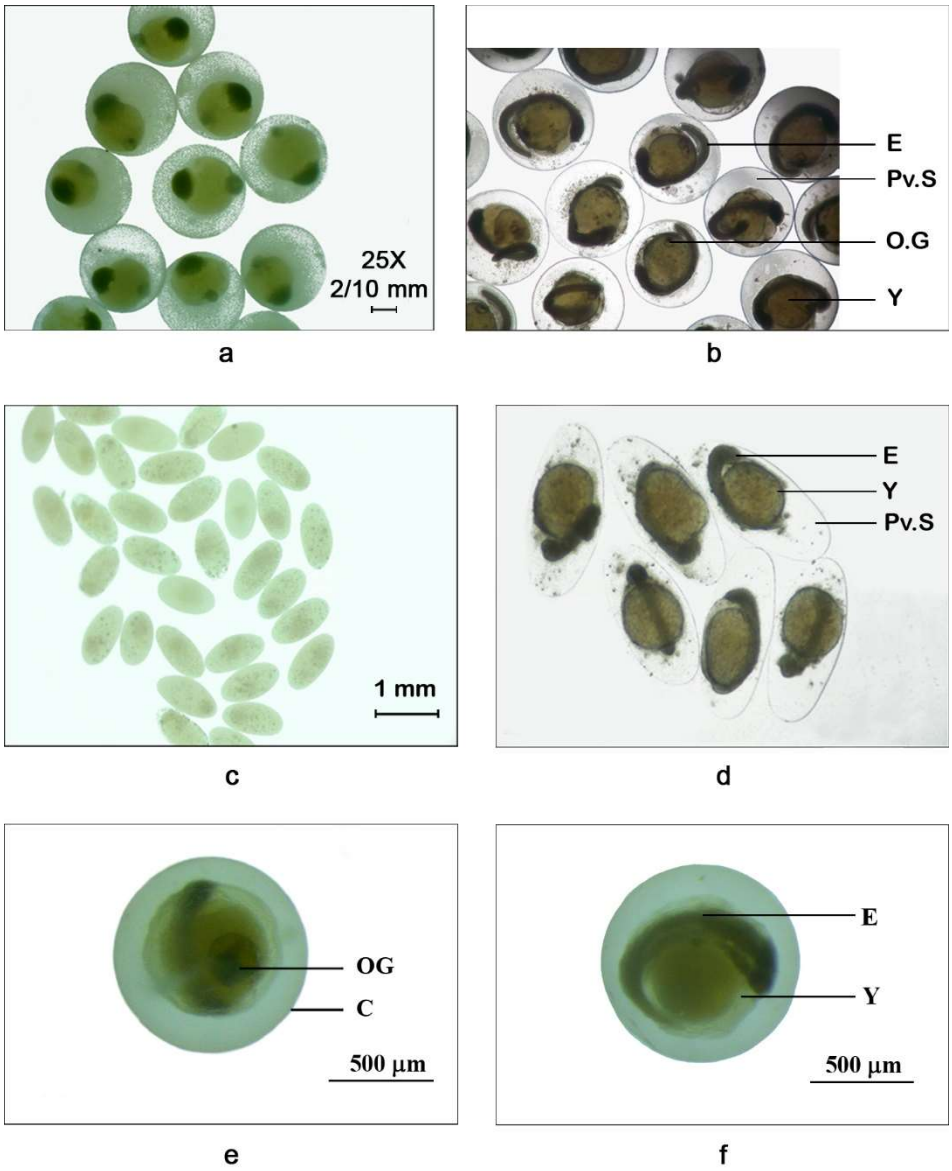
Morphometric parameters	**N**	***df***	**F**	**p**
LJXSL	139	2	70.81	<0.001
HLXSL	139	2	217.5	<0.001
BDXSL	139	2	2105	<0.001
EDXHL	101	2	856.3	<0.001

SL, Standard length: LJL, Lower jaw length: HL, Head length: BD, Body depth: ED, Eye Diameter: N, Number of samples:

Table 3.6 Pairwise comparisons using Post-hoc Analysis (Tukey-HSD)

Relationship B/W	p
E. devisi X *S. longiceps*	0.0079723
R. kanagurta X *S. longiceps*	0.0000000
*R. kanagurta*X *E. devisi*	0.0000000

PLATE 1



Eggs of Sardinella longiceps, Encrasicholina devisi and Rastrelliger kanagurta.

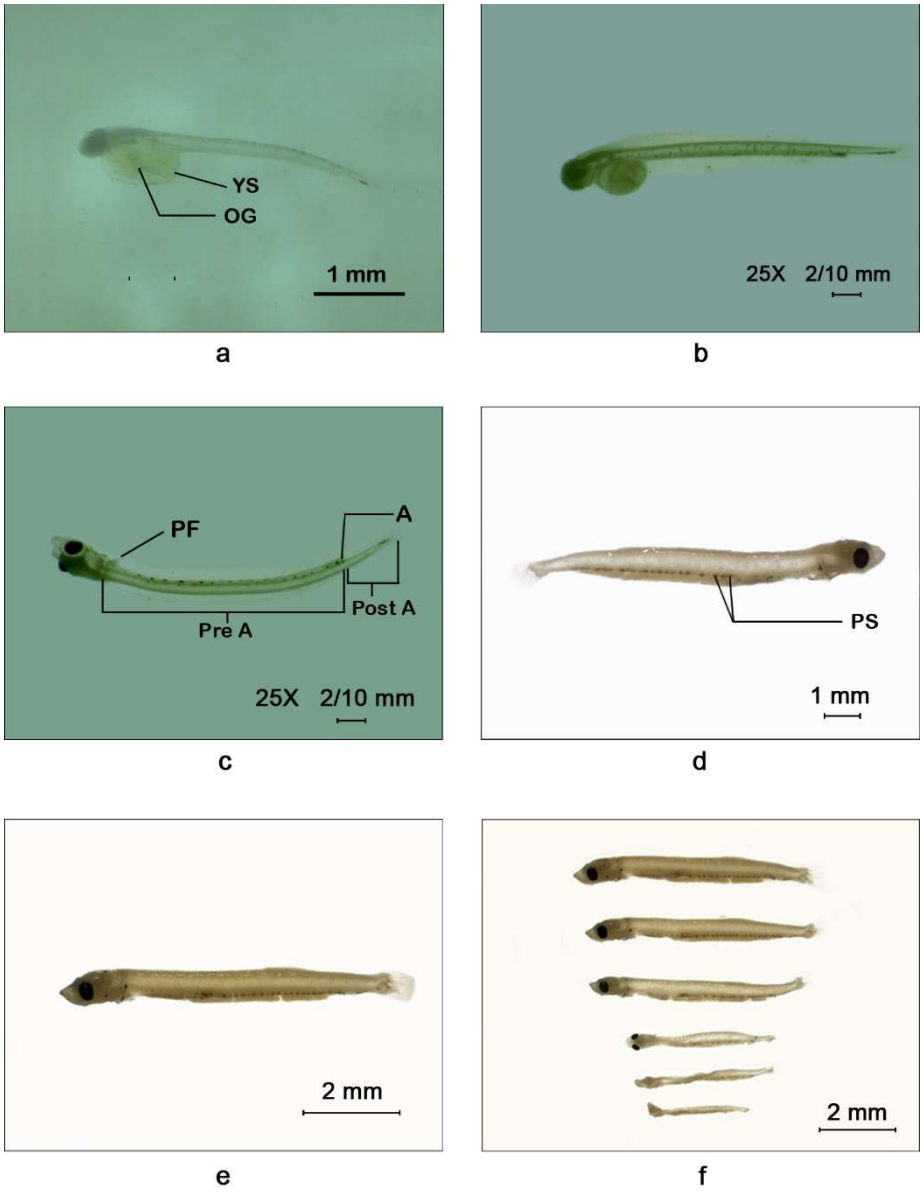
(a) Early stage egg and (b) Late stage egg of *Sardinella longiceps*

(c) Early stage egg and (d) Late stage egg of *Encrasicholina devisi*

(e) Middle stage egg and (f) Late stage egg of *Rastrelliger kanagurta*

[Y-Yolk, OG – Oil globule, C – Chorion, E – Embryo, Pv.S – Perivitelline space]

PLATE 2

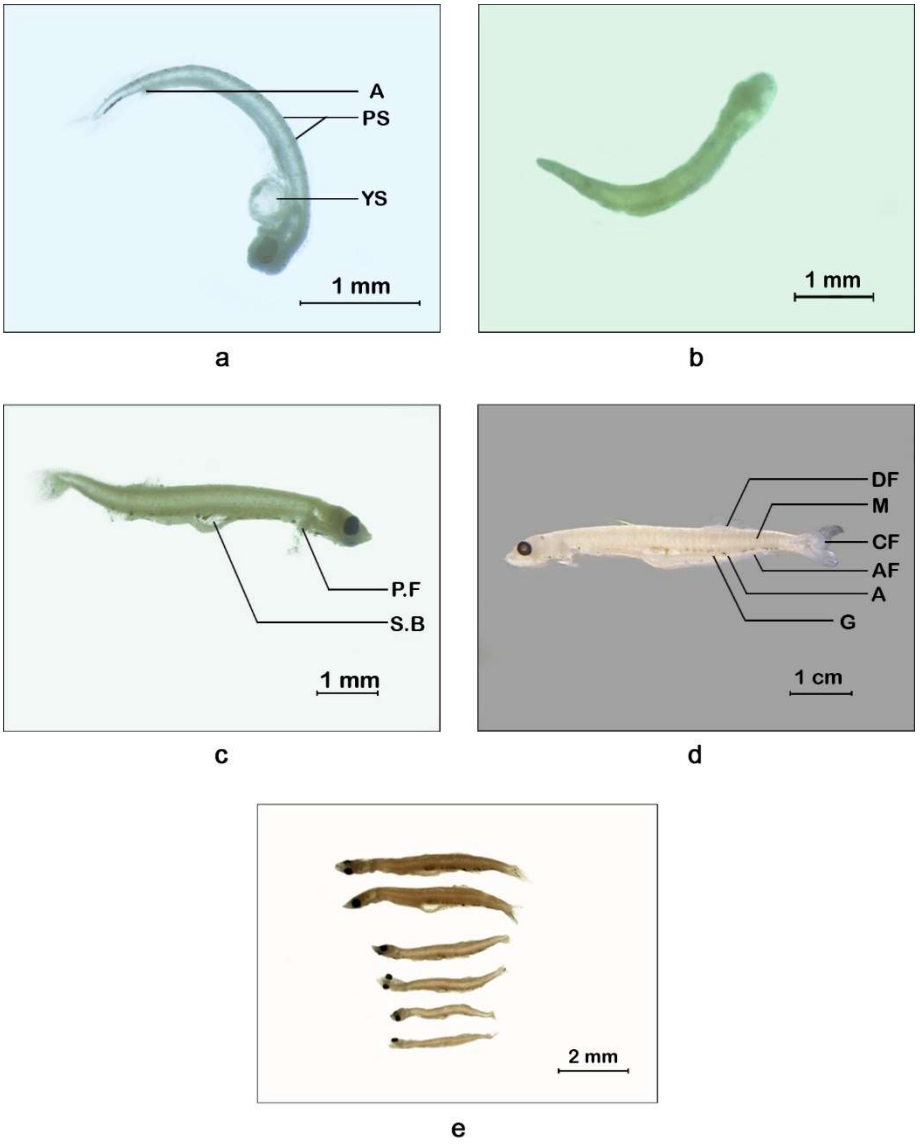


Developmental stages of *Sardinella longiceps*

a) Yolk sac stage
b) Late yolk sac stage
c) Preflexion stage
d) Flexion stage
e) Post flexion stage
f) Developmental stages

[YS-Yolk sac, OG – Oil globule, PF-Pectoral Fin, A – Anus, Pre A – Pre Anal length, Post A – Post Anal Length, PS-Pigment Spots]

PLATE 3

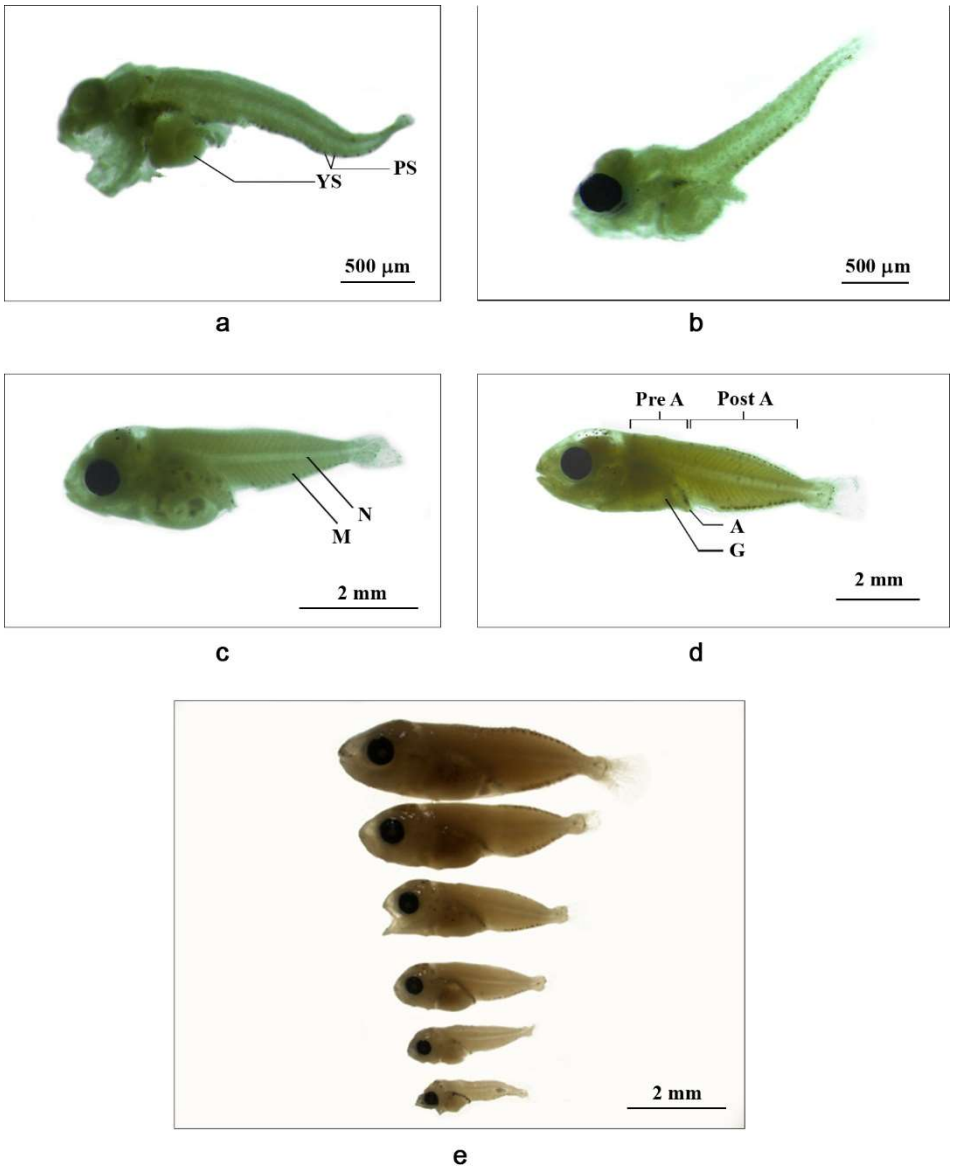


Developmental stages of *Encrasicholina devisi*

a) Yolk sac stage
b) Pre-flexion stage
c) Flexion stage
d) Post flexion stage
e) Developmental stages

[YS-Yolk sac, PF-Pectoral Fin, A – AnusPS-Pigment Spots, SB-Swim Bladder, G-Gut, M-Myomere, DF-Dorsal Fin, AF-Anal Fin, CF-Caudal Fin].

PLATE 4



a b c d e

Developmental stages of *Rastrelliger kanagurta*

a) Yolk sac stage
b) Pre-flexion stage
c) Flexion stage
d) Post flexion stage
e) Developmental stage

[YS-Yolk sac, M-Myomere, G-Gut, N-Notochord, A – Anus, Pre A – Pre Anal length, Post A – Post Anal Length, PS-Pigment Spots

Chapter 4

Distribution and Abundance of Eggs & Larvae

4.1 *Introduction*

The relevance of ichthyoplankton studies in explaining the variations in abundance of fish populations is receiving more attention recently. The distribution and abundance of fish eggs and larvae have a direct relation to the recruitment potential of an area and therefore can serve as a valuable aid in the management of fisheries (Manickasundarm *et al*., 1987; Siraimeetan and Marichamy, 1988; Doyle and Ryan, 1989; Nilssen *et al*., 1994; Munk *et al*., 1995; Samina and Shahid, 2001). Fish larvae have a horizontal dynamic distribution affected by factors such as adult spawning behaviour, water mass movements, localized larval mortality and larval behaviour (Smith 1981; Hounde 1982; Jahn and Lavenberg 1986). Ichthyoplankton abundance of a region can indicate the seasonal and annual variation in spawning activity of fishes (Katsuragawa *et al.,* 2011) and can determine the duration of breeding season. It also indicates the size of spawning stocks, and its variability may be associated to fluctuations in fishery recruitment. Ichthyoplankton studies provide details on interrelationships between different fish species during their early life stages (Nonaka *et al.,* 2000).

Major ichthyoplankton surveys along the south west coast of India are Carlsberg foundation's Dana Expedition (1928-30) covering the Indian Ocean (Jones and Kumaran, 1963). Ichthyoplankton survey by the Indo - Norwegian Project (1953) covering south west coast of India and Lakshadweep sea (Jones and Kumaran, 1964, Silas, 1974). Another major study in the Indian Ocean and adjacent seas was the International Indian Ocean Expedition (1960-64), (Peter, 1968, 1977; Lalithambika Devi, 1969). As part of the assessment of the Pelagic Fish resources of the area extending from Ratnagiri to Tuticorin, systematic ichthyoplankton surveys were carried out by UNDP/FAO, Pelagic Fishery Project, Cochin (1971 – 1979) (Anon, 1974; 1976) over the shelf and adjacent waters along the south west coast of India. This survey indicated that all the major pelagic fishes spawned in the shelf waters along the south west coast of India and their peak spawning was during summer monsoon with a secondary peak during north east monsoon for some species (George, 1989). Recently MR-LR programme of CMLRE conducted Ichthoplankton surveys along Arabian Sea (Binu, 2003) and SEAS (SreeRenjima *et al.,* 2017).

Some of the studies on the quantitative aspects on eggs and larvae of oil sardine, anchovies and Indian mackerel in the SEAS upwelling system are described here. Balakrishnan (1957) noted the eggs and larvae of *Rastrelliger kanagurta* from the coastal waters off Vizhinjam. Bennet (1967) studied the seasonal abundance of juveniles of *Rastrelliger kanagurta* from Vizhinjam waters. Balakrishnan and Rao (1971) reported the post larval and juvenile stages of *Rastrelliger kanagurta* from the waters of Vizhinjam and Kannur. Silas (1974) reported the occurrence of *Rastrelliger kanagurta* larvae from the coastal waters of south west coast of India. Lazarus (1976 and 1985) reported the occurrence of *Sardinella sirm* and

Sardinella longiceps larvae from Vizhinjam. George (1988) reported mackerel larvae from the nearshore waters of Vizhinjam during May and October. The distribution of *Sardinella longiceps* eggs and larvae, *Stolephorus sp* larvae and mackerel larvae along SEAS were described by George (1989). Binu (2003) reported *Sardinella longiceps* larvae during summer monsoon from the coastal waters off Kannur. *R.kanagurta* larvae were also reported by Binu (2003) from 8°N to 17°N with highest concentration at 10°N coastal station. Binu (2003) observed the presence of *Stolephorus sp* from 7.5°N to 11.5°N during March to July. Sree Renjima *et al.,* (2017) studied the distribution and abundance of mackerel larvae along SEAS.

In the present study, the distribution and abundance of eggs and larvae of oil-sardines, anchovies and Indian mackerel in the upwelling systems of SEAS during Summer Monsoon (SM) season are explained. The SEAS upwelling system is delineated to 3 distinct zones namely the South Zone extending from Cape to Kollam (7°N to 9°N), the Central Zone (Kollam to Kozhikode; 9°N to 11.5°N) and the North Zone covering areas of SEAS north of Kozhikode (>11.5°N). For the purpose of the present study, the SM upwelling season is differentiated into 3 phases viz; Phase-1 (On set Phase) from mid-May to mid-June, Phase-2 (Peak Phase) from mid- June to mid- July and Phase-3 (Receding phase) beyond mid-July. Though the actual commencement and duration of these phases varies with the zones, for the sake of consistency, these phases are treated uniformly throughout the study area. Egg and larval abundance is represented in Nos.10m^{-2} area (Smith and Richardson, 1977) by multiplying the volume of water filtered with the Mixed Layer Depth (MLD).

4.2 *Results*

4.2.1. *Abundance and Distribution of Fish eggs*

A total of 234 Bongo collections were analysed to describe the abundance and distribution of ichthyoplankton of oil sardines, mackerel and anchovies in the SEAS, during the 3 phases of SM. For the entire survey period, the abundance of eggs was higher in the south zone (68.91%) compared to the central (23.9%) and north (7.18%) zones. Mean abundance of fish eggs during phase-1 of SM from the entire collection (76 Bongo stations) were 1586.06±5349.19 nos.10m^{-2}. For phase-2 was it was 156590.38±9072.44 nos.10m^{-2} (20 Bongo stations) and for phase-3, the values were 83.39±295.42 nos.10m^{-2} (138 Bongo stations). It was observed that eggs were more abundant in the coastal stations (64.92%) than in shelf (33.29%) and oceanic (1.79%) regions. Numerical abundance of fish eggs along the three zones during different phases of monsoon are depicted in Table 4.1. Fish egg abundance along coastal, shelf, oceanic stations in the three zones are represented in Table 4.2. Percentage composition of fish eggs in North zone, Central zone and South zone during different phases of SM are depicted in figure 4.1. Spatial distribution and abundance of fish eggs along SEAS during different phases of monsoon is illustrated in figure 4.2 (a and b).

During phase-1 of SM 2009, the total abundance of fish eggs were 85123 nos.10m^{-2} and the mean abundance was 2182.64±6219.9 nos.10m^{-2}. The fish eggs were highest in the central zone 71.8% followed by 17.5% south zone and 10.7% north zone. During phase-1 SM 2010, the total abundance of fish eggs were 37712 nos.10m^{-2} and the mean abundance was 3142.74±9818.5 nos.10m^{-2}. The survey covered only SZ. In phase-1 SM 2015, the total fish eggs recorded were highest in the south zone (41.67%) followed by central (36.76%)

and north zone (21.43%). The total abundance of fish eggs was lower (8596 nos.10m^{-2}) among the three surveys of phase-1 and mean abundance was 343.86±502.44 nos.10m^{-2}.

In phase-2 of 2010, the fish eggs total abundance was 21394 nos.10m^{-2}. The mean abundance during this period was 1069.7±2223.4 nos.10m^{-2}. The fish eggs were highest in the south zone (62.1%) than north zone (5.2%) and central zone (32.7%).

During phase-3 of SM 2009 the total abundance of fish eggs was 152876 nos.10m^{-2}. Of this 95.1% was from SZ, 2% from CZ & 2.9% was from the NZ. The mean abundance was 2388.7±9968.6 nos.10m^{-2}. In the year 2013, phase-3 operations yielded 6634 eggs.10m^{-2} of which 96.3% was from the NZ, 3.4% from CZ and the rest (0.3%) from SZ. In the year 2015, a total of 74602 eggs.10m^{-2} were obtained with a mean abundance of 2487±9611 nos.10m^{-2}. NZ with 70.6% dominated in egg abundance followed by the SZ (20.3%) and the CZ (9.1%).

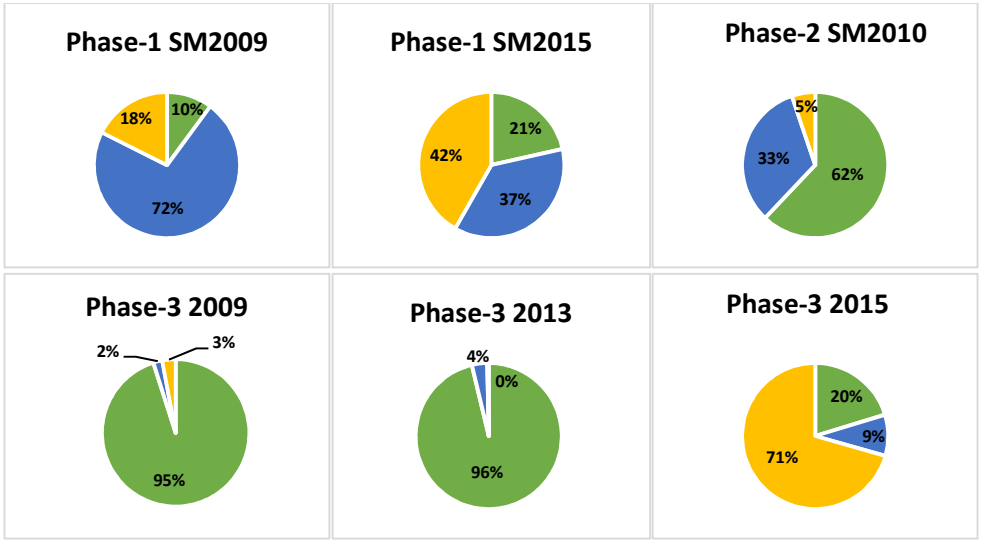


Fig.4.1. Percentage composition of Fish eggs in North zone, Central zone and South zone during different phases.

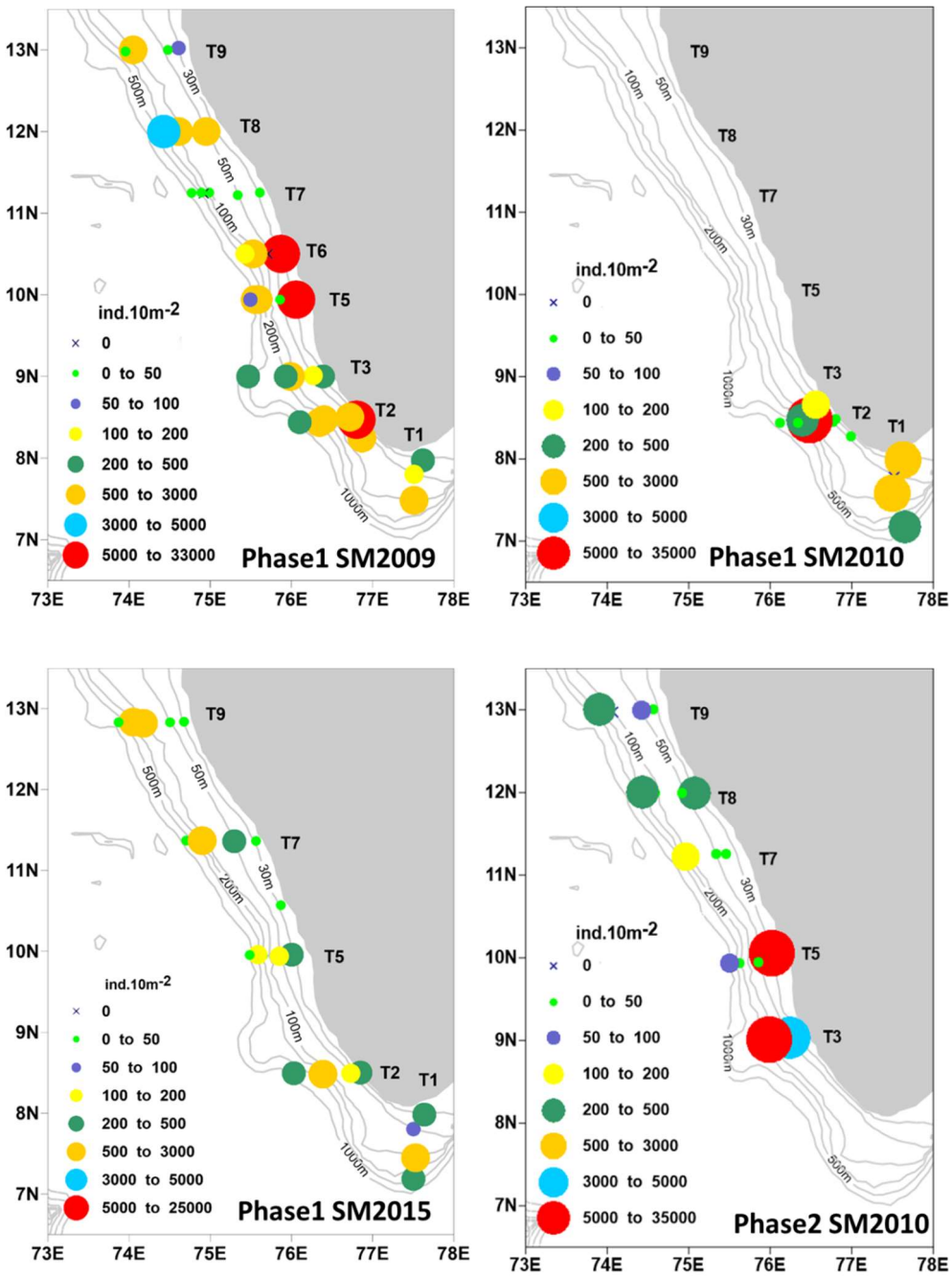


Fig. 4.2 (a) Distribution and abundance of Fish eggs along SEAS during different phases of SM

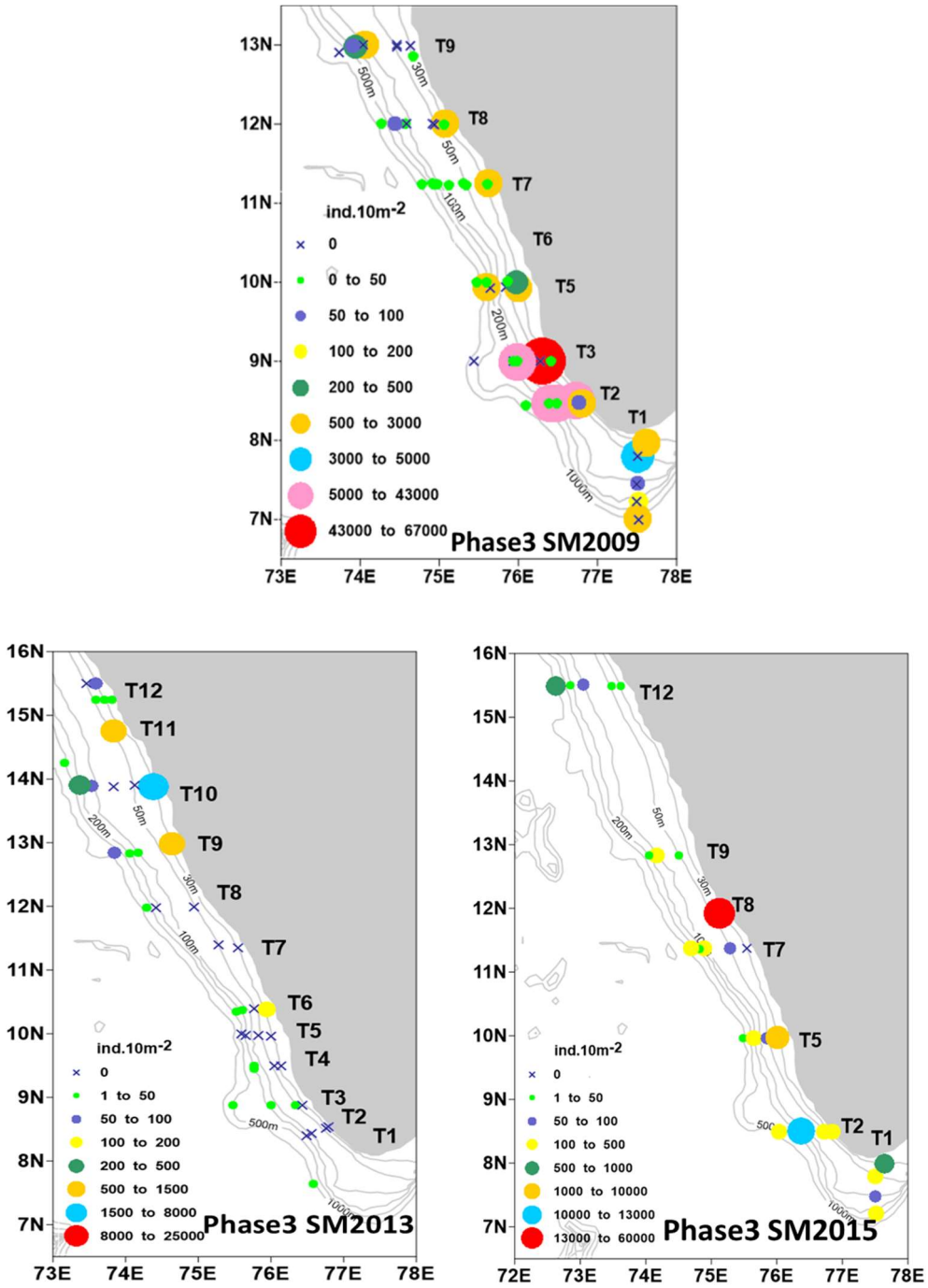


Fig. 4.2 (b) Distribution and abundance of Fish eggs along SEAS during different phases of SM

4.2.2. *Distribution and abundance of Sardinella longiceps eggs*

Oil sardine eggs were recorded from Valappad (CZ) from 30m depth station (10°30.045'N; 75°52.065'E) on 12th June 2009 (19:45hrs.) at a distance of 18.7kms from shore. Eggs were at its early stage. The density of the eggs recorded was 666 nos.10m^{-2}. Eggs of oil sardines were conspicuously absent in the SZ during the entire study period (2009 to 2015, phase-1 to 3 of SM) except in one collection off Trivandrum 50m (8°21.43'N; 76°51.84'E) which was undertaken at 8:00hrs on 25th May, 2017 (phase-1), subsequent to the original study period. Bongo net full of sardine eggs (83848 ind.10m^{-2}) in the middle stages of development were obtained [Figure 4.3(d)].

During the second phase of SM sardine eggs were not represented in the Bongo catches from all the 3 zones. In phase-3 of year 2009, middle staged oil sardine eggs (215 nos.10m^{-2}) were recorded from off Kannur (12°00.587'N; 75°04.330'E) on 6th August (full moon day) at 18.25hrs and eggs in advanced stages (108 nos.10m^{-2}) from off Kozhikode (11°15.112'N; 75°37.006'E) on the following day (17.48hrs), presumed to be spawned north off Kozhikode. A major spawning ground of Oil sardine was found off Kannur, (11°55.007'N, 75°07.634'E), 30m depth station during August 2015. Spawning occurred during early morning (5:00am) in the presence of mild rain on the 12th of August, couple of days prior to the new moon day. The density of sardine eggs was observed as 51640 nos.10m^{-2}. Eggs were at early stage of development. Oil sardine eggs were also collected from off Kochi 30m depth station on 15 Aug 2015 at 14:25hrs. The density of eggs was 5871 nos.10m^{-2}. These eggs were in the middle stage of development. It was observed that predominantly oil

sardine eggs were found in the coastal waters within a distance of 30km. from the shore. Sardine eggs were not represented in the bongo collections from SZ during the late phase of monsoon. Likely spawning grounds of *Sardinella longiceps,* is represented in Figure 4.3(a).

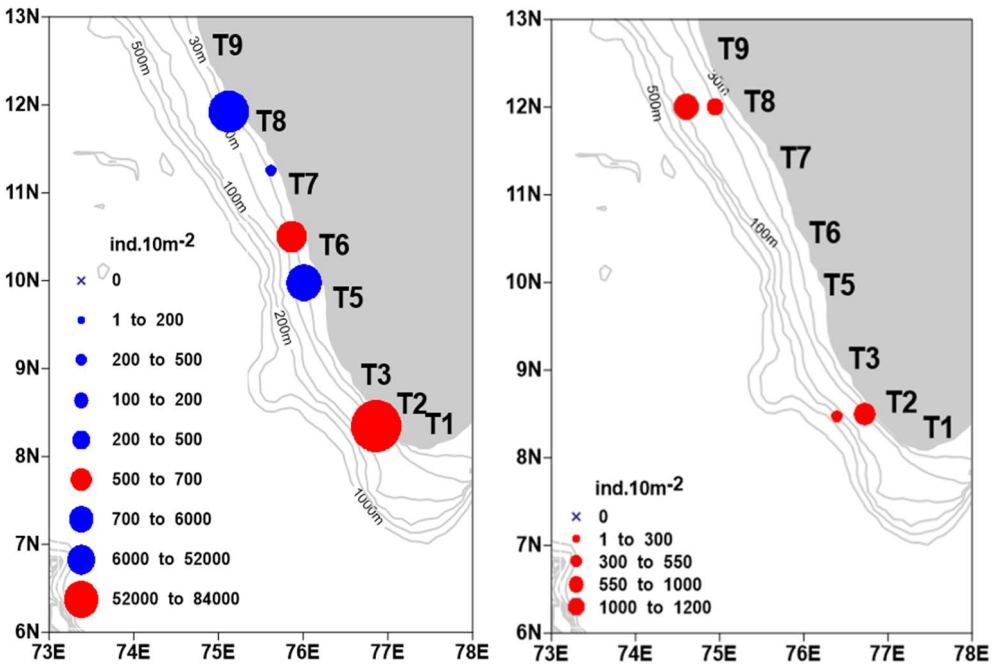
4.2.3. *Distribution and abundance of Encrasicholina devisi eggs*

Encrasicholina devisi eggs were observed during the first phase of monsoon only. Spawning grounds of *E. devisi* was observed at the 30m station off Valappad, (10°57'N, 75°87'E) on 03 Jun 2015 at a distance of 14.72km from the coast. The density of eggs was 98 nos.$10m^{-2}$. The eggs were observed during early morning hours (05:52am). *Encrasicholina devisi* eggs were also recorded from off Trivandrum (8°50'N, 76°85'E) 30m depth station on 28 May 2015. The density of eggs was 435 nos.$10m^{-2}$. Eggs were collected from a location 6.11km off the coast at 07:50hrs. Eggs were also obtained (530 nos. $10m^{-2}$) from the 50m station off Kannur on 11 Jun 2009. All the batches of eggs were in the early stage of development. Likely spawning grounds of *E.devisi* are represented in Fig. 4.3(b).

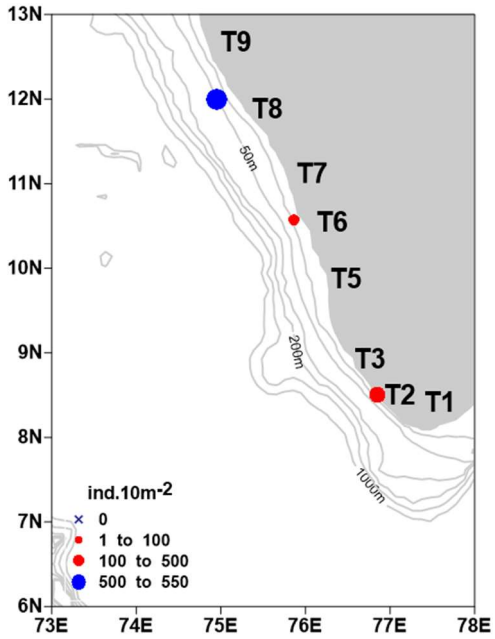
4.2.4. *Distribution and abundance of Rastrelliger kanagurta eggs*

Rastrelliger eggs were collected during phase-1 SM from off Trivandrum 50m (8°30.085'N; 76°43.374'E) and 200m stations (8°27.902'N; 76°24.012'E). The densities of eggs were 975 nos.$10m^{-2}$ and 255 nos.$10m^{-2}$ respectively. These eggs were collected on 02 Jun 2009 at 4:55hrs. and 2:10hrs. Both sets of eggs collected were at early stage of development. Mackerel eggs were also collected from off Kannur 50m

(11°59.918'N; 74°57.031'E) and 100m (11°59.796'N; 74°36.427'E) stations on 11 Jun 2009 at 20:43hrs. and 23:15hrs. respectively (total of 1710 eggs). Egg densities recorded were 530 nos.10m^{-2} (50m stn.) and 1180 nos.10m^{-2} (100m station). Advanced stages of eggs were present in these collections. Most likely spawning grounds of *R.kanagurta* are represented in Fig. 4.3(c).



(a) (b)



(c)

Fig. 4.3 Spawning grounds of a) *Sardinella longiceps*, b) *Encrasicholina devisi* and c) *Rastrelliger kanagurta* along SEAS during different phases of SM. Phase 1 SM denoted by blue dots and Phase-2 SM denoted by red dots.

Fig.4.3(d) Eggs of *Sardinella longiceps* collected from Trivandrum 50m, May 2017

4.2.5. *Distribution and Abundance of Fish larvae*

During the study period, peak abundance of fish larvae were recorded from the south zone (77.6 %) compared to the north (13.8%) and central zones (8.6%). The mean abundance of fish larvae during phase-1 of SM was as 1153.00±5228.67 ind.10m^{-2} followed by phase-3 (230.01±1026.42 ind.10m^{-2}) and phase-2 (145.62±481.89 ind.10m^{-2}). Fish larvae were more abundant in the coastal stations (60.18 %) than shelf (34.46 %) and oceanic (5.36 %) stations during the whole survey period. Percentage composition of fish larvae in North zone, Central zone and South zone during different phases of SM are depicted in figure 4.4. Distribution and abundance of fish larvae along SEAS during different phases of SM is illustrated in figure 4.5 (a and b). Numerical abundance of fish larvae in the three zones of SEAS during different phases of monsoon are given in Table 4.1. Larval abundance in the coastal, shelf and oceanic stations of the three zones are depicted in Table 4.2.

Of the 39 stations covered during the onset phase of SM 2009, the total abundance of larvae was 60179 ind.10m^{-2} and the mean abundance was 1543.05± 6841.55 ind.10m^{-2}. Fish larval abundance was highest in the south zone contributing 85.6%, central zone (6.25 %) and north zone (8.07%). Fish larvae were present in almost all the stations sampled. Maximum abundance of larvae was recorded at the Kollam 50 m station (42933 ind.10m^{-2}) of SZ. In general, larval density was highest in the coastal stations (76.77%) followed by the shelf (14.18%) and oceanic stations (9.04%). During the initial phase of SM 2010, a total of 44614 ind.10m^{-2} were recorded from 12 stations, with a mean abundance of 3717.8±7893.1 ind.10m^{-2}. The percentage of larval abundance was higher in shelf (56.16%) and coastal (42.29%) stations. Maximum abundance

(24220 ind.10m^{-2}) was recorded at the Trivandrum 100m station. During the early initial phase (May) of SM 2015, the survey was conducted at 25 stations. The fish larval mean abundance was lower 114.49 ±143.11 ind.10m^{-2}. Majority of the larvae where from the south zone (59.57%) followed by the central (27.46%) and north zones (12.96%). Peak larval density in this survey was recorded from Trivandrum 200 m depth station. Larvae were more abundant in the coastal (44.13%) stations than shelf (39.94%) and oceanic (15.93%). In the three cruise surveys conducted during the initial phase of SM (FORV SS: 267, 276 & 340) it was observed that peak abundance (90.9%) of larvae were recorded in the south zone. Larval abundance was almost negligible in the north (4.8%) and central zones (4.3%).

In phase-2 of year 2010, a total of 3033 larvae. 10m^{-2} were collected representing SZ (20.6%), CZ (60.8%) and NZ (18.6%).

In the wane phase (p-3) of SM, 3 surveys were conducted along SEAS during the years 2009, 2013 and 2015 (FORV SS: 270, 272 317 & 343). The 2009 survey covered 64 stations along the SEAS recording 10871 larvae.10m^{-2}. The mean abundance of larvae recorded was 169.9±761.7. ind.10m^{-2}. Maximum density of larvae were recorded from Mangalore 200 m station (6009 ind.10m^{-2}) and the Kannur 50 m station (495 ind.10m^{-2}). The larval abundance was high in the NZ contributing 75.7%, low in the CZ (3.6%) and medium (20.7%) in the SZ. Majority of the larvae (62.21%) were from the coastal stations followed by shelf stations (33.36%) and oceanic stations (4.39%). During 2013 survey (FORV SS: 317), which covered 44 stations along SEAS, the mean density of fish larvae recorded was 177.49±612.86 ind.10m^{-2}. The

percentage contribution of larval abundance was higher in the CZ (54.57%) followed by NZ (42.89%). Fish larvae were almost absent in the south zone (2.55%). Maximum density of larvae was recorded from Alleppey 30m station (3565 ind.10m^{-2}). 93.02% of the total larvae were from coastal stations. In the 2015 survey of 30 stations a total of 1569 larvae.10m^{-2} were obtained with a mean density of 52.3 larvae.10m^{-2} and near equal abundance in the SZ (45.3%) and NZ (43.5%).

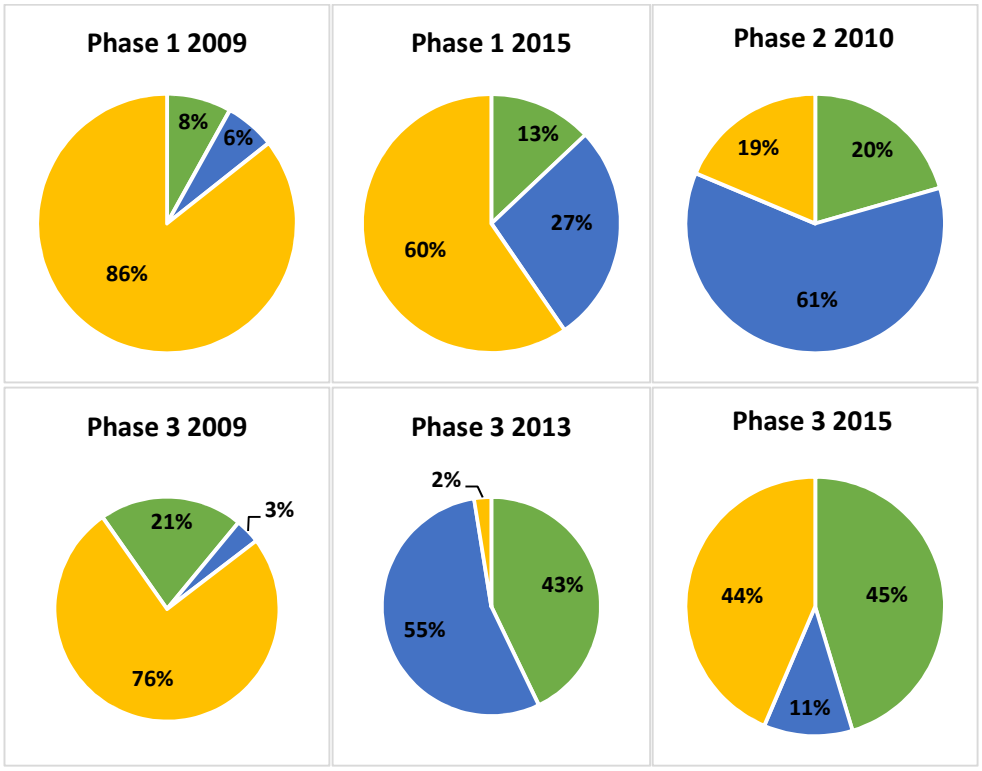


Fig.4.4 Percentage composition of Fish larvae in North zone, Central zone and South zone during different phases

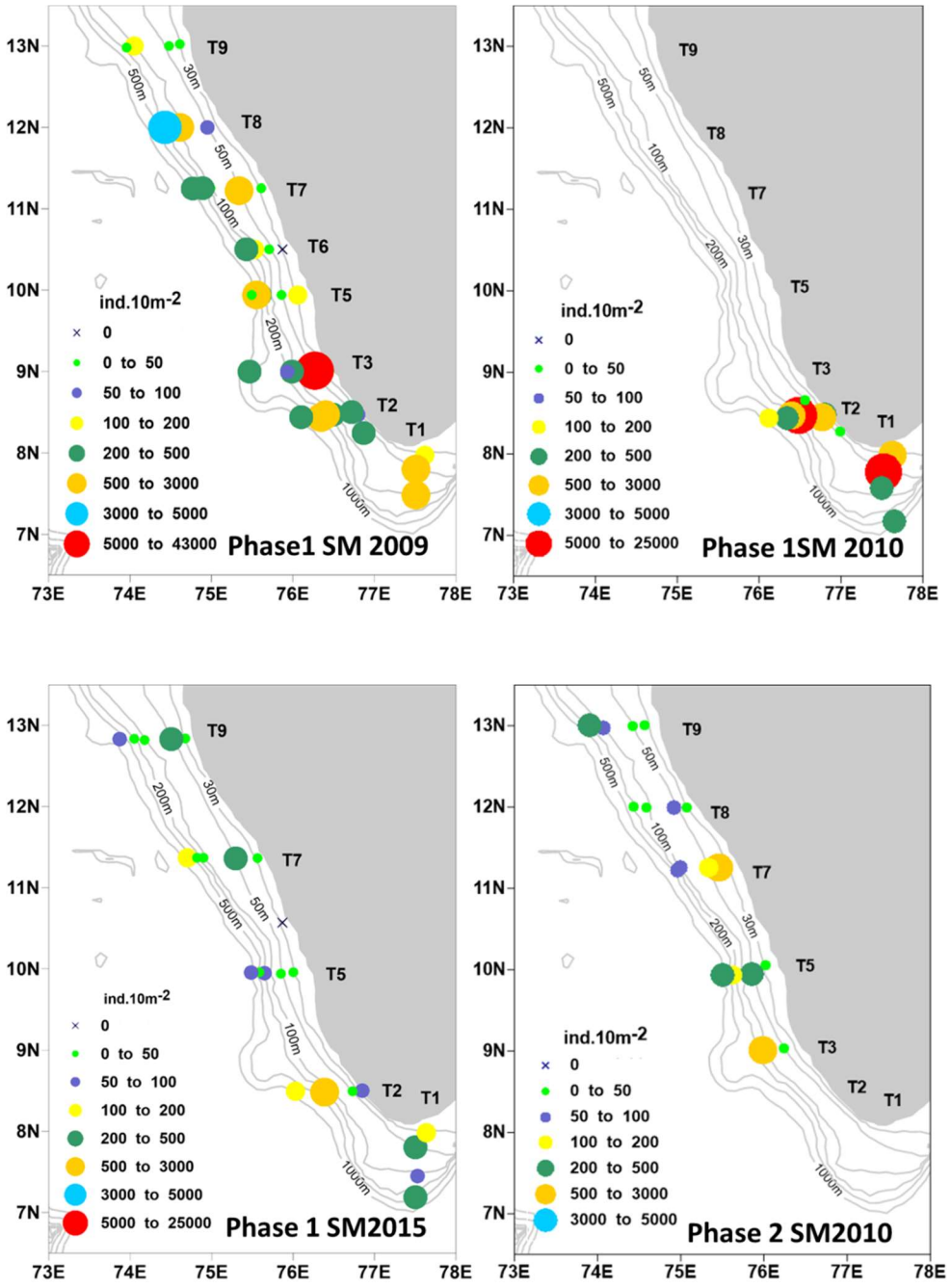


Fig. 4.5(a) Distribution and abundance of Fish larvae along SEAS during different phases of SM

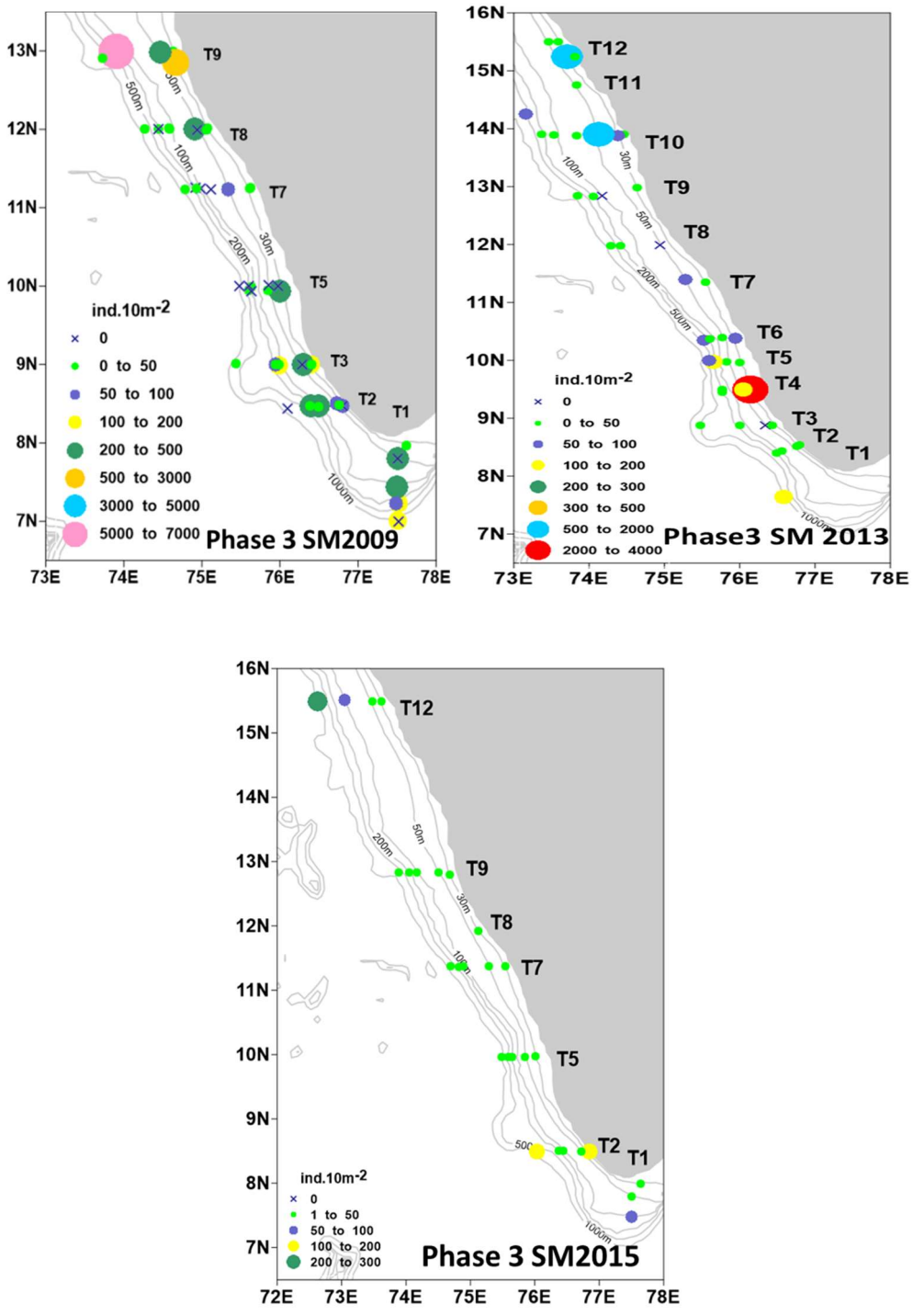


Fig. 4.5(b) Distribution and abundance of Fish larvae along SEAS during different phases of SM

4.2.6. *Distribution and abundance of Sardinella longiceps larvae*

Out of a total of 234 stations covered during the whole study, oil sardine larvae were obtained from only 59 stations. Nevertheless, oil sardine larvae formed the major contributor (55.5%) to the total larval abundance in SEAS during the whole study. The mean abundance of oil sardine larvae during phase-1 of SM was 698.19±4413.72 ind.10m^{-2} followed by phase-2 (72.78±300.90 ind.10m^{-2}) and almost absent in phase-3 (3.22±11.69 ind.10m^{-2}). In the entire survey, oil sardine larvae were present in high proportion in the SZ (92.5%) as compared to the NZ (4.9%) and CZ (2.6%). Large proportion of Oil sardine larvae were obtained from shallower than 50m (85.23%) isobaths followed by the 50m to 100m (11%). Larvae were almost absent in the 100m to 200m (1.77%) and 200m to 500m (1.95%) isobaths. Percentage composition of *Sardinella longiceps* larvae in North zone, Central zone and South zone during different phases of SM are depicted in figure 4.6. Distribution and abundance of *Sardinella longiceps* larvae in the SEAS during different phases of SM season is shown in figure 4.7 (a and b). Numerical abundance of oil sardine larvae and larval abundance along coastal, shelf, oceanic stations along the three zones during the different phases of SM are depicted in Table 4.1 and Table 4.2 respectively. Numerical abundance of pre flexion, mid flexion and post flexion stages of *Sardinella longiceps* larvae along coastal, shelf and oceanic stations in the three zones during different phases of monsoon are presented in Table 4.3.

Investigations on zonal variations in oil sardine larvae during onset phase of SM 2009 (mid-May to mid-June) reveal that the total abundance of the oil sardine larvae during this phase was 42948

ind.10m^{-2}, with a mean of 1101.24±6394.17 ind.10m^{-2}. Larvae were recorded only from the SZ (100%) with nil occurrences in the CZ & NZ. Kollam transect of SZ recorded exceptionally high density of larvae with maximum abundance in the surface waters off Kollam 50m (39980 ind.10m^{-2}) station. All the developmental stages were observed in this larval aggregation dominated by flexion stages. However, larvae in the Trivandrum transect (SZ) was dominated by pre flexion and early flexion stages with the near shore stations entirely occupied by pre flexion stages. The abundance of the larvae increased towards the offshore stations with highest value of 783 ind.10m^{-2} dominated by flexion stages, recorded from the surface waters of 200m depth station off Trivandrum transect. Sardine larvae were absent in Cape 30m station (SZ) while post flexion and flexion stages dominated in the rest of the stations of Cape transect. Oil sardine larvae were present only in the SZ leaving the CZ and NZ of the study area totally devoid of its presence from mid- May to mid-June. During phase-1 SM 2010 season, peak abundance of oil sardine larvae was at from Cape 50m (15657 ind.10m^{-2}) and Trivandrum 100m (7147 ind.10m^{-2}) stations. Both the stations were dominated by flexion and post flexion stages. The mean abundance of *Sardinella longiceps* larvae was 1991.5±2998.12 ind.10m^{-2} and the total abundance was 23901 ind.10m^{-2}. During phase-1 of 2015 SM season, the mean abundance of oil sardine larvae was 6.31±21.35 ind.10m^{-2} and the total abundance 158 ind.10m^{-2} of which 148 ind.10m^{-2} were from the SZ and the rest were from the NZ. The larval abundance was high in the Cape 50 (101 ind.10m^{-2}) and 30m (47 ind.10m^{-2}) stations and almost absent in rest of the SZ transects. NZ

accounted for the remaining 10 larvae.10m^{-2}. In all the three collections of phase-1, flexion stage of larvae dominated.

The second phase of the SM is represented by year 2010 with 20 larvae.10m^{-2} from 20 bongo operations. Though the data is not sufficient for meaningful interpretations, the general trend in the data set show a shift in larval abundance from the SZ (40%), to CZ (15%) and NZ (45%).

From the 138 bongo operations conducted in phase-3, a total of 5708 larvae.10m^{-2} were recorded. NZ dominated in larval abundance (63%), followed by CZ (32.6%) and SZ (4.4%) which indicates a clear northward shift in larval abundance. In the phase-3 collections of year 2009 the total abundance of the *Sardinella longiceps* larvae was found to be 711 with NZ accounting for 79.2%, SZ for 17.6% and CZ for 3.2% occurrences. Peak values were recorded in NZ at Kannur 50m station (454 ind.10m^{-2}) predominated by flexion and pre flexion stages. Off the Mangalore 30m station 59 ind.10m^{-2} abundance was recorded, dominated by larvae in the flexion stage. Only pre flexion larvae (23 ind.10m^{-3}) were recorded from Calicut (CZ) 50m. In the south zone, larvae were recorded at Cape 50m station with a mixed proportion of all the developmental stages. During phase-3, 2013 SM, *Sardinella longiceps* larvae were the most abundant (4714 ind.10m^{-2}) among the fish larvae constituting about 71.04% of the total fish larvae recorded in this survey. They were abundant towards the northern transects than the southern part. Aggregation of *Sardinella longiceps* larvae were observed at coastal stations off the northern transects Bhatkal (1833 ind.10m^{-2}) and South Goa (1134 ind.10m^{-2}). High abundance was also recorded from Alleppey (1420 ind.10m^{-2}) located in the central zone. At Goa station 95% of the total

larvae were constituted by *Sardinella longiceps* larvae while at Bhatkal 99% was constituted by sardine larvae. At Off Alleppey 30m coastal station, 92% of the total larvae were that of oil sardines and majority of them were in its pre flexion stages. Flexion stages dominated at off Bhatkal and Goa. In phase-3, 2015, the total abundance of oil sardine larvae were 283 ind.10m^{-2}. of which the SZ account for 127 ind.10m^{-2} (45%) and CZ account for 137 ind.10m^{-2} (48%) and NZ 19 ind.10m^{-2} (7%).

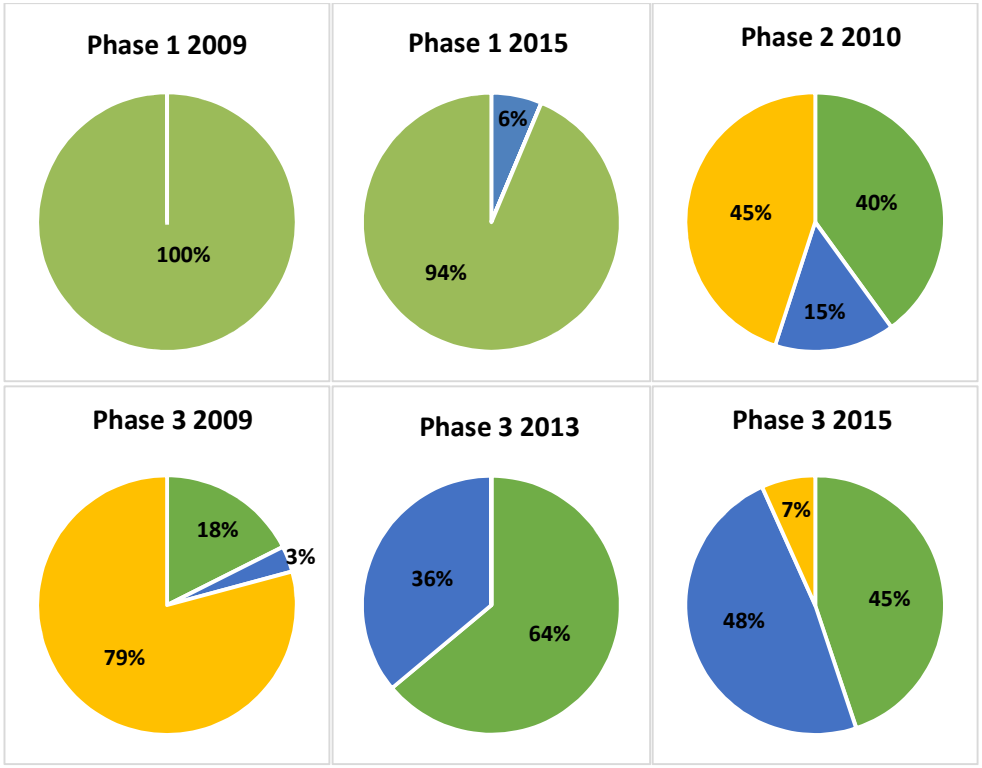


Fig.4.6 Percentage composition of *Sardinella longiceps* larvae in North zone, Central zone and South zone during different phases

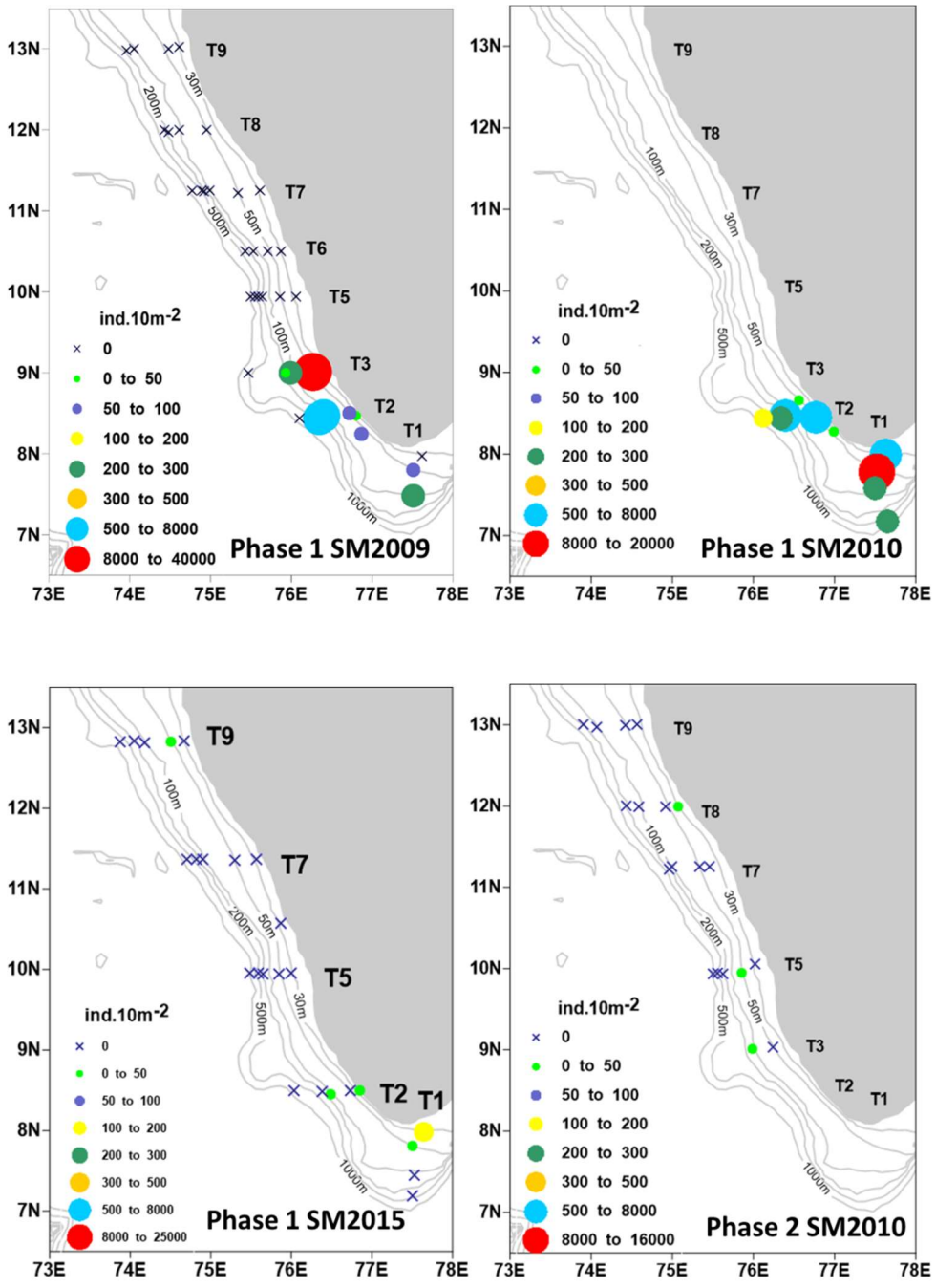


Fig. 4.7(a) Distribution of *Sardinella longiceps* larvae along SEAS during different phases of SM

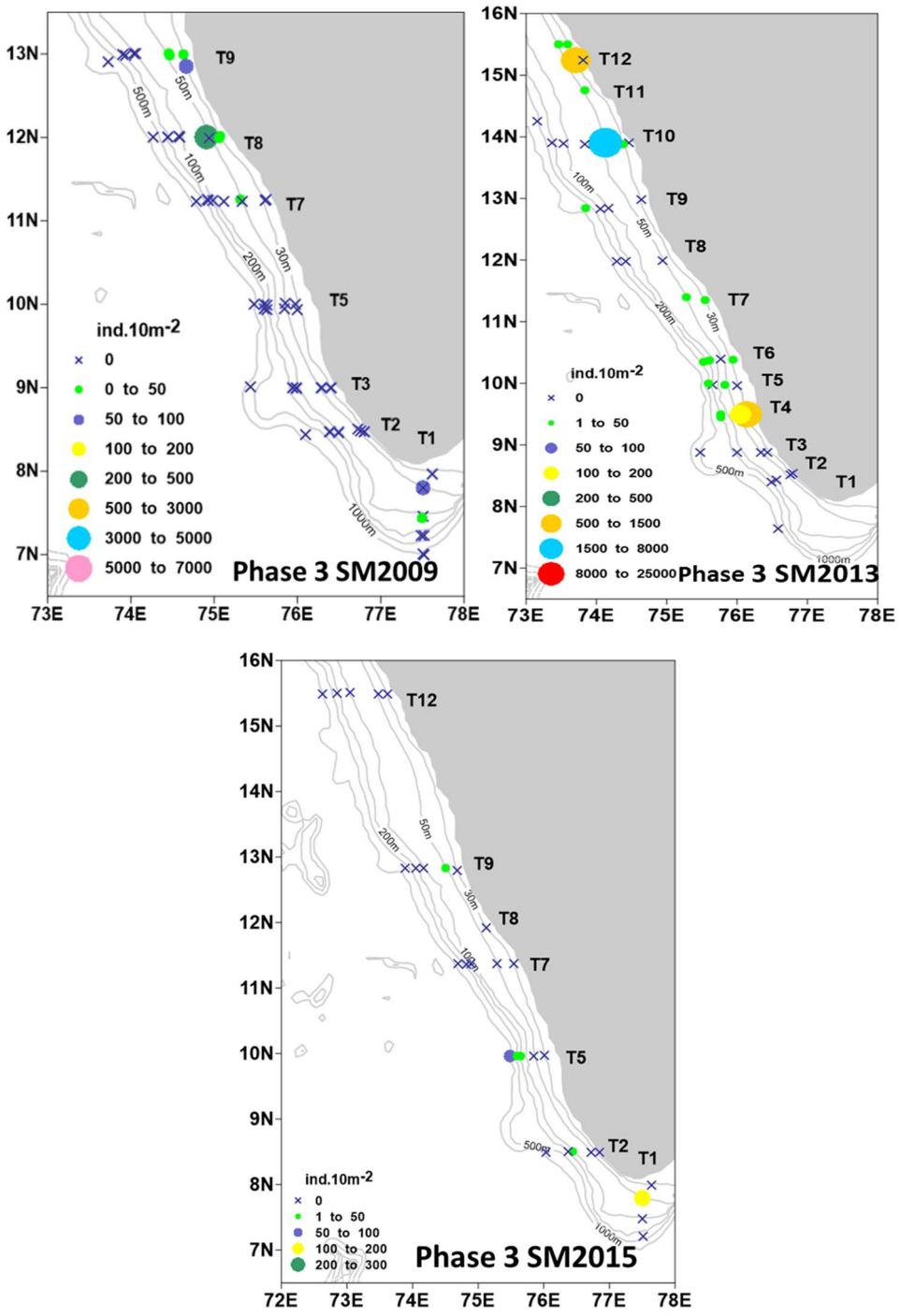


Fig. 4.7(b) Distribution of *Sardinella longiceps* larvae along SEAS during different phases of SM

4.2.7. *Distribution and Abundance of Encrasicholina devisi larvae*

Encrasicholina devisi larvae contributed 7.2% to the total fish larval abundance of SEAS during the whole study period. A total of 9479 larvae were recorded from 68 stations out of the 234 stations surveyed. The mean abundance of *E.devisi* larvae showed a decreasing trend from phase-1 SM (105.2 larvae.10m^{-2}) to phase-2 SM (53.4 larvae.10m^{-2}) and phase-3 SM (3.04 larvae.10m^{-2}). Annual abundance was near equal in the SZ (39.5%), CZ (29.9%) and NZ (30.6%). It was observed that *Encrasicholina devisi* larvae were present in higher numbers at 200m (33.58%) followed by 50m (24.23%), 100m (21.43%), 500m (12.35%) and 20-30m (7.38%) isobaths. They were almost absent in 1000m (0.91%) isobath. Numerical abundance of *E.devisi* larvae along three zones during the different phases of SM are given in Table 4.1. Table 4.2 shows the larval abundance along coastal, shelf and slope stations. Numerical abundance of developmental stages of *E.devisi* larvae along coastal, shelf and oceanic stations in the three zones during different phases of SM are detailed in Table 4.3. Percentage composition of *E.devisi* larvae in North zone, Central zone and South zone during different phases of SM are depicted in figure 4.8.

Spatial distributions of *E.devisi* larvae along SEAS during different phases of SM is illustrated in figure 4.9 (a and b).

During phase-1 of SM 2009, the total abundance of *E.devisi* larvae was 5720 ind.10m^{-2} and the mean abundance was 146.66±346.45 ind.10m^{-2}. Higher values of larval abundance were recorded between Kannur and Calicut transects. Both these transects together contributed 59.53% of the *E.devisi* collection. Pre flexion, flexion and post flexion

stages were present at Calicut 50m (1123 ind.10m^{-2}) station while only flexion and post flexion stages occurred in the Kannur 100m depth (550 ind.10m^{-2}) and 200 m depth (1711 ind.10m^{-2}) stations. It was observed that these larvae were present in varying densities in all transects up to Mangalore thereby showing a wide range in distribution. During phase-1 SM 2010, the mean abundance of the larvae was (81.8±233.9) and the total abundance was 982 ind.10m^{-2}. Peak density of larvae was recorded from Trivandrum 100m depth station (817.80 ind.10m^{-2}) composed of flexion and post flexion stages. During May 2015, larvae of *E.devisi* had a mean abundance of 48.81±120.56. Maximum number of larvae were recorded from Off Trivandrum 200 m (549 ind.10m^{-2}) station. Pre flexion, flexion and post flexion stages were present at this station. The total number of *E.devisi* larvae collected during the cruise was 1220 ind.10m^{-2}. The larvae were observed in all transects and all zones in varying numbers indicating their wide distribution. Calicut 50m (265 ind.10m^{-2}) station had pre flexion, flexion and post flexion stages. It was noted that larvae were abundant in shelf waters of north and south zone while in central zone larvae were more abundant in the coastal waters.

During phase-2 of SM 2010, the total abundance of larvae reduced to 1067 ind.10m^{-2} and the mean abundance was 53.35±125.96 ind.10m^{-2}). The larvae were moderately high at Kochi 200 m station consisting of pre flexion and flexion stages. They showed poor abundance in the SZ (5.2%) and NZ (3.4%). During phase-3 of year 2009 only 9 larvae were obtained, all from the CZ. In phase-3 of SM 2013, the total abundance of *E.devisi* larvae was slightly higher (55 ind.10m^{-2}) and the mean abundance was (1.24±4.87 ind.10m^{-2}). The highest density recorded in this survey was

from Kochi 200 m (30 ind.10m^{-2}) station which was dominated by flexion and post flexion stages. A few numbers of post flexion larvae were present in the shelf waters off Trivandrum and off Valappad. From Cape 1450m depth station 9 ind.10m^{-2} in post flexion stage was recorded.

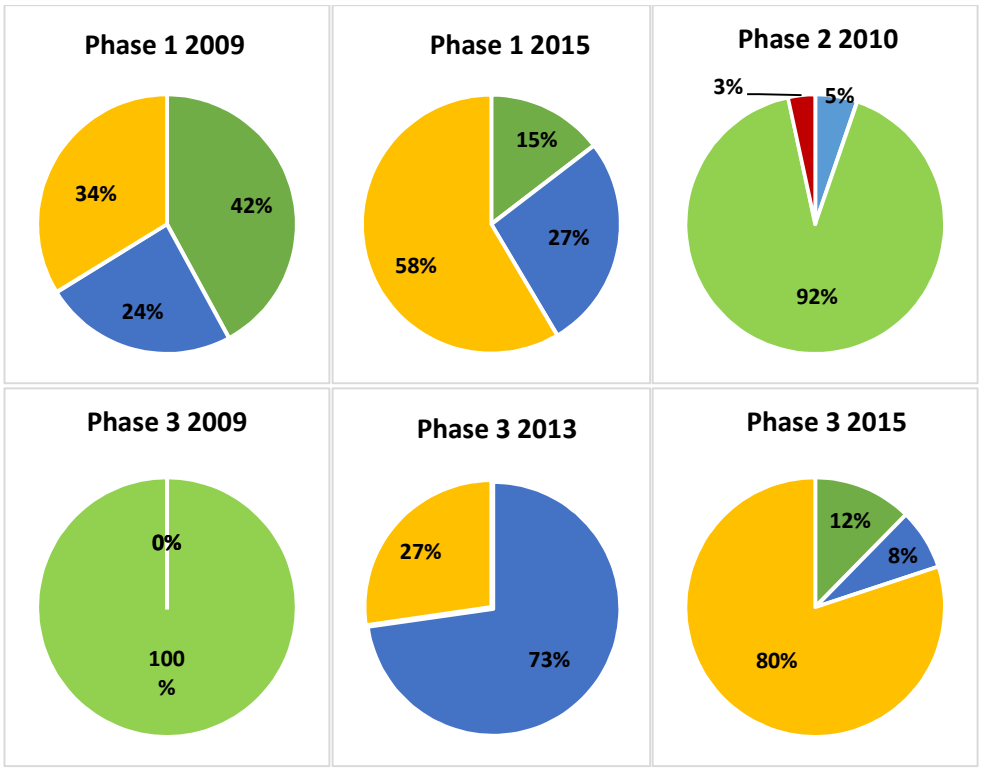


Fig.4.8 Percentage composition of *Encrasicholina devisi* larvae in North zone, Central zone and South zone during different phases

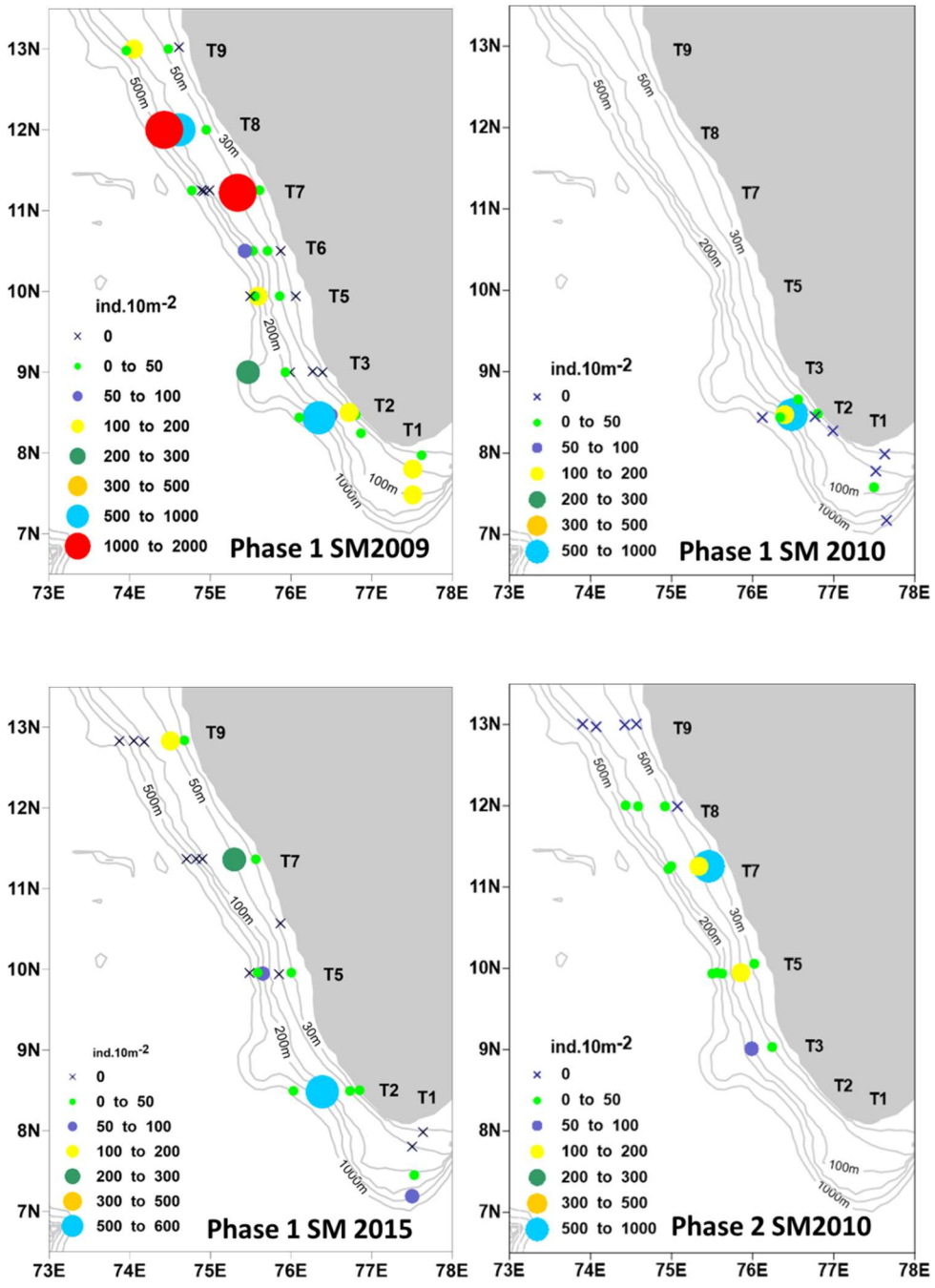


Fig. 4.9(a) Distribution of *Encrasicholins devisi* larvae along SEAS during different phases of SM

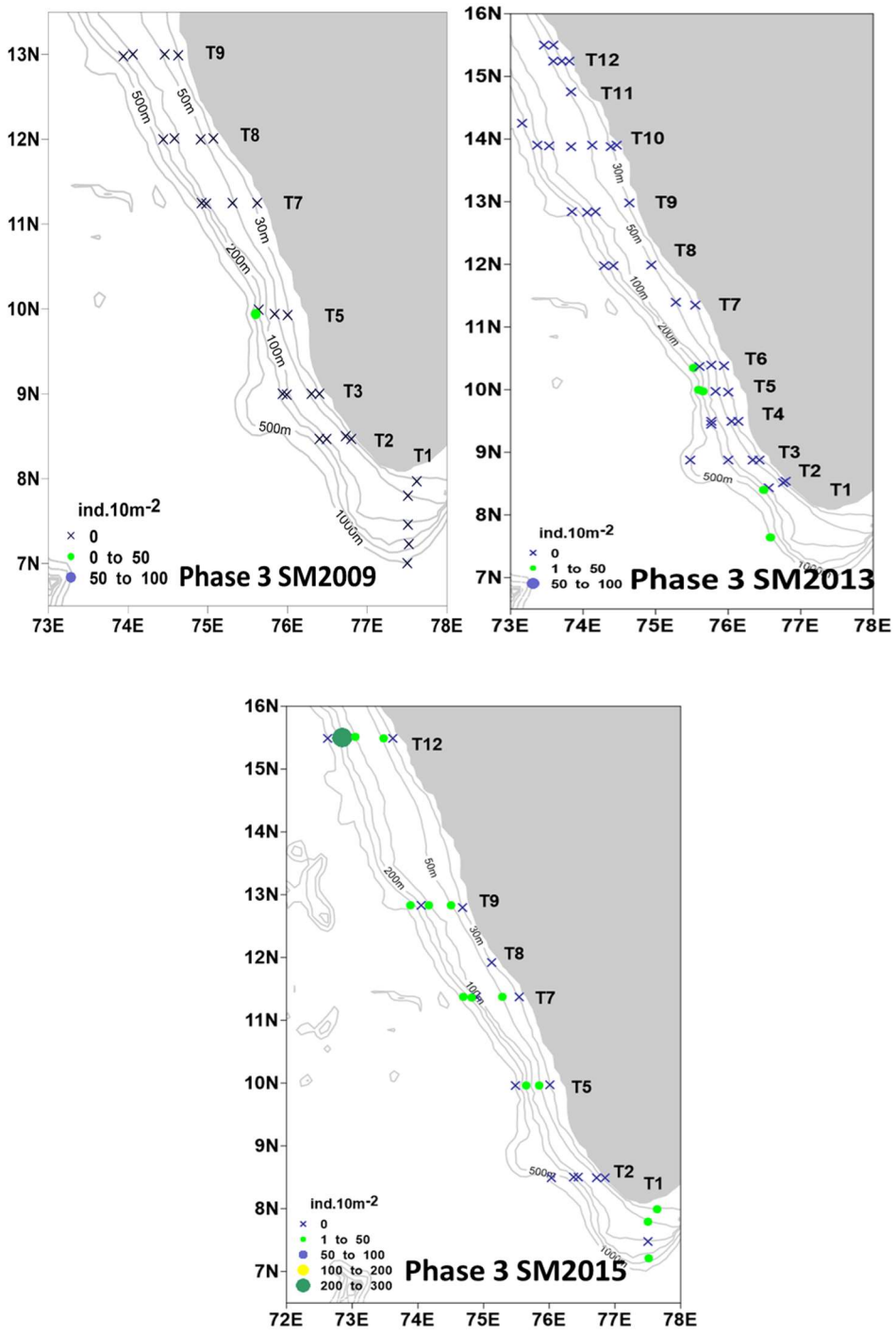


Fig. 4.9(b) Distribution of *Encrasicholins devisi* larvae along SEAS during different phases of SM

4.2.8. *Distribution and Abundance of Rastrelliger kanagurta* larvae

Rastrelliger kanagurta larvae contributed only 7.05% to the total larval abundance during the entire study. Of the total 5125 larvae.10m^{-2} recorded in the present study, 88.3% were from the SZ, 10.5% from the NZ and only 1.2% was from the CZ. It was observed that 68.57% of *R. kanagurta* larvae were recorded from 50m depth station. They were also present in the collections from other depth zones of the shelf such as the 100m station (14.08%), the 200m (13.47%) station, the 500m station (2.19%) and below 40m stations (1.56%). They were completely absent at 1000m isobath except for few (0.14%) larvae in the post flexion stage recorded from 1450m station of Cape transect. The abundance of *R.kanagurta* larvae during phase-1 of SM was 90.6% of the total of 5125 larvae recorded with the SZ contributing 91.64%, NZ 8.32% and CZ 0.04%. During phase-2, larval abundance was 5.6% of the total, with SZ recording maximum abundance (87.7%), followed by the NZ (9%) and CZ (3.3%). Larval abundance in phase-3 was the lowest (3.6%) with NZ accounting for 69.3%, CZ 26.9% and the SZ with 3.8% of phase-3 larval abundance (182 larvae.10m^{-2}). Numerical abundance of *R.kanagurta* larvae along the three zones during the different phases of SM are given in Table 4.1. Larval abundance along coastal, shelf and slope stations are depicted in Table 4.2. Numerical abundance of developmental stages of *R.kanagurta* larvae along coastal, shelf and oceanic stations are given in Table 4.3. Percentage composition of larvae in North zone, Central zone and South zone during different phases of SM are depicted in figure 4.10. Distribution and abundance of *R.kanagurta* larvae along SEAS during different phases of SM is illustrated in figure 4.11 (a and b).

During phase-1 2009, the total abundance of larvae was 3992

ind.10m^{-2} and the mean abundance was (102.35±471.42 ind.10m^{-2}). The larvae were abundant in the south zone (90.28%) compared to north (9.67%) and central (0.05%) zones. An aggregation of Rastrelliger larvae was observed at Kollam coastal station (2935 ind.10m^{-2}). Pre flexion (23.47%), flexion (54.26%) and post flexion (22.27%) stages were present in this station. Pre flexion stages were also recorded from Cape and Trivandrum transects in the south zone. Mackerel larvae were present in all the southern transects and noticeably absent in the CZ & NZ except for a single station off Kannur (200m station) from where 386 ind.10m^{-2} constituting preflexion and flexion stages was recorded. During the year 2010, in the onset phase of SM the abundance of mackerel larvae (445 ind.10m^{-2}) was found to be much lower than the previous year. All the larvae where recorded from the south zone. The highest larval abundance of (377 ind.10m^{-2}) was observed at Trivandrum 100m depth station dominated by post flexion (66.84%) stages. Larvae were also present in good numbers at Kollam 100m station, constituting preflexion (3.03%), flexion (81.44%) and post flexion (15.90%) stages. In phase-1 of year 2015 also, mackerel larvae (205 larvae.10m^{-2}) were recorded exclusively from the SZ with nil representation from the CZ & NZ. In phase-2 of year 2010, larval abundance was relatively low (301 larvae.10m^{-2}) and mostly (264 larvae.10m^{-2}) restricted to the SZ. A few larvae were present at Calicut 200m (10 ind.10m^{-2}) and Kannur 50m (27 ind.10m^{-2}) stations.

During the wane phase (P-3) of SM (August 2009) the mean abundance of larvae reduced to 1.00±5.42 ind.10m^{-2} and the total abundance was 69 ind.10m^{-2}. Larvae were present in all the CZ & NZ transects in few numbers, but absent in the SZ. At Kannur 50m station maximum density (41 ind.10m^{-2}) was observed. This collection was dominated by flexion stages (70.24%) followed by preflexion (17.68%)

and post flexion (11.78%). In phase-3 of 2013 the mean abundance of mackerel larvae was 2.53±8.39 ind.10m^{-2} and total abundance recorded was 111 ind.10m^{-2}. An aggregation of preflexion (10.74%), flexion (84.55%) and postflexion (5.75%) stages of mackerel larvae were observed at Goa coastal station (30m depth), which was the highest abundance observed in the survey (52 ind.10m^{-2}). 70.27% of the total mackerel larvae were recorded from north zone followed by 23.42% in central zone and 6.30% in south zone. Mackerel larvae were recorded in very low numbers (2 larvae.10m^{-2}) with a mean abundance of 0.07±0.37 in phase-3 of year 2015.

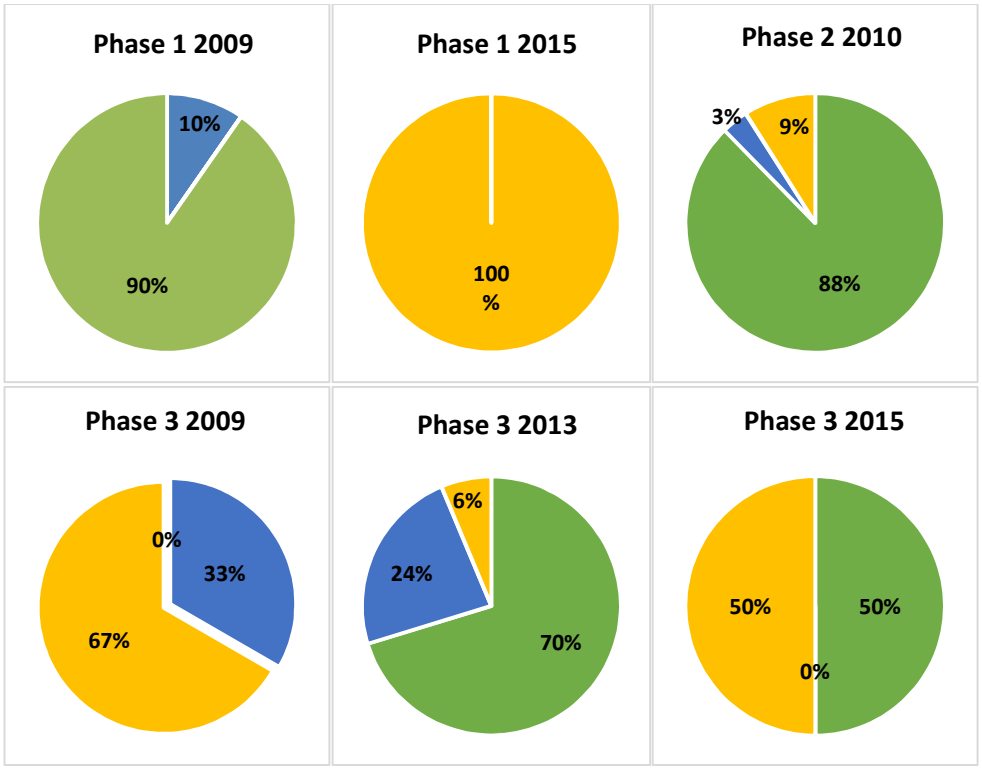


Fig.4.10 Percentage composition of *Rastrelliger kanagurta* larvae in North zone, Central zone and South zone during different surveys

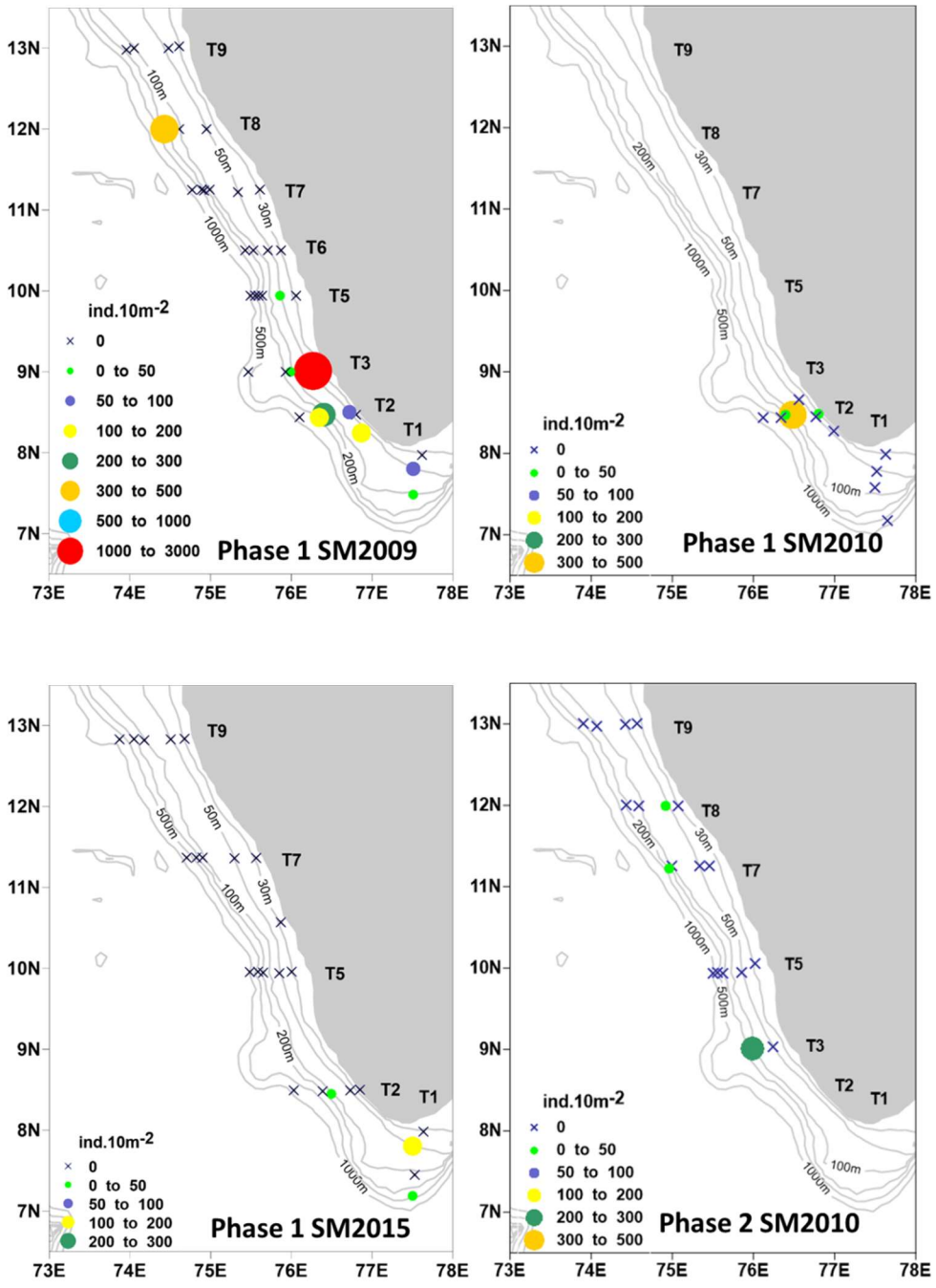


Fig. 4.11(a) Distribution of *Rastrelliger kanagurta* larvae along SEAS during different phases of SM

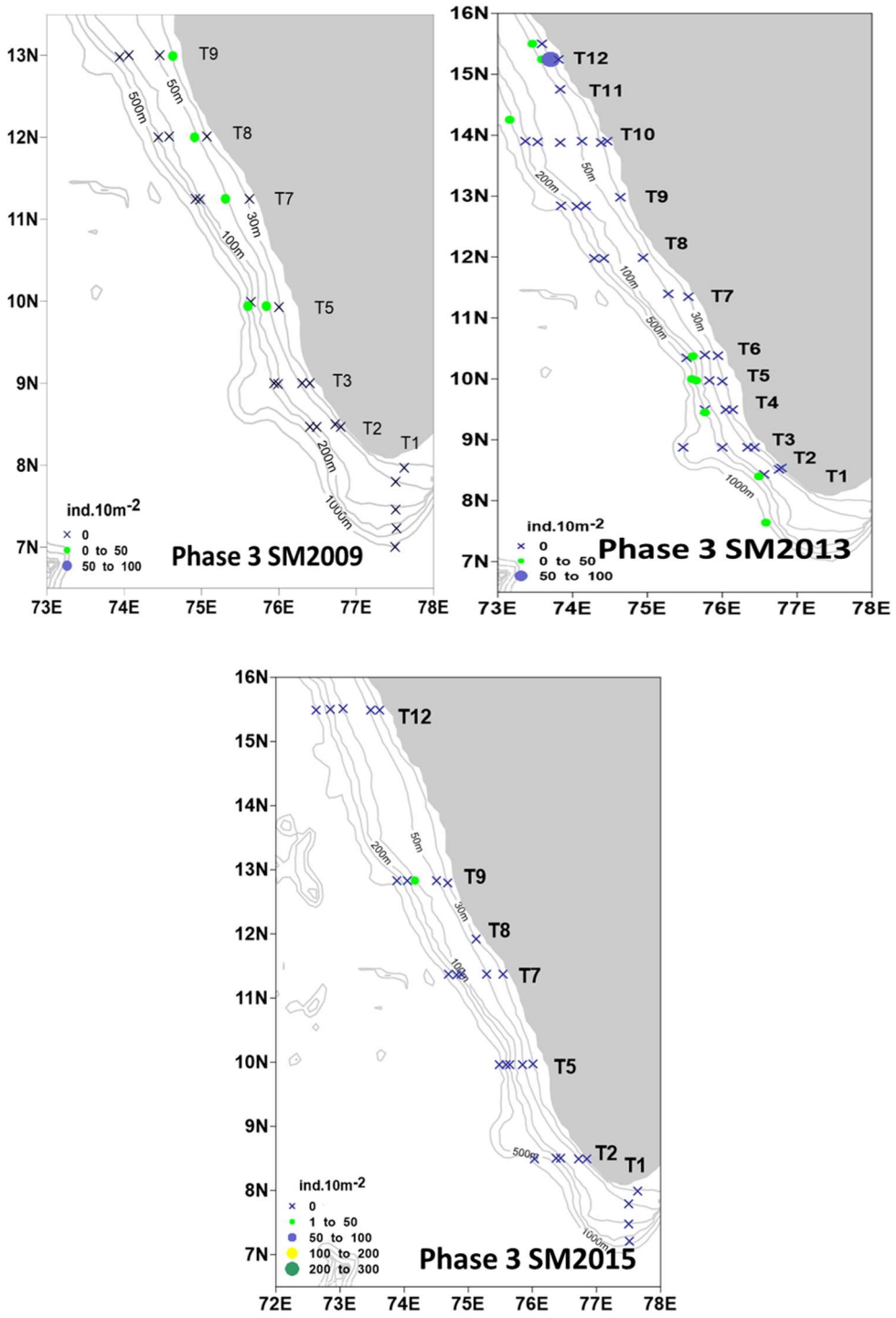


Fig. 4.11(b) Distribution of *Rastrelliger kanagurta* larvae along SEAS during different phases of SM

4.3. *Discussion*

Wide variations in the seasonal / inter-annual and spatial distribution / abundance of the total and species specific counts in fish eggs and larvae were observed during the study period. The large range in abundance of eggs & larvae (Table 4.1 & 4.2) result in asymmetrical distributions and standard deviations that are significantly higher than mean values, unlike the normal Gaussian distribution. Nevertheless, the mean values obtained could capture the overall trends in abundance and distribution to facilitate meaningful interpretations.

During the SM upwelling season in SEAS, numerical abundance of fish eggs were maximum in the SZ (68.91%), followed by the CZ (23.9%) and NZ (7.18%), which implies that most fish species prefer the SZ over the other two zones for the purpose of spawning. Though wide inter-annual variations in egg abundance are evident in the data set (Table 4.1), the general trend indicates maximum abundance of eggs in the SZ during phase-1 & 2 of SM corresponding to the onset and peak phase of the upwelling season in SEAS. It is well established that the upwelling process in SEAS is initiated in the SZ and advances northwards as the season progresses (Bakun *et al.,*1998; Smitha *et al.,*2008). The observed high abundance of eggs is therefore consistent with the overall environmental set up of the SZ that may perhaps stimulate spawning in most fish species. Unlike phase-1 & 2, the wane phase of SM upwelling (phase-3) do not show any consistent pattern in egg distribution and abundance. In the year 2009, NZ dominated in the abundance of fish eggs, whereas in 2013 and 2015 high egg abundance was recorded from the CZ.

In the 234 Bongo collections made over the seven year sampling period (2009 to 2015), a total of 58500 sardine eggs were obtained from the 30m isobaths of the CZ (6645 eggs) & NZ (51855 eggs). Sardine eggs were totally absent from the 50m isobaths onwards, which indicates that oil-sardine is predominantly a coastal spawning species. Nair (1960) have reported *Sardinella longiceps* larvae from Calicut with maximum abundance from June to August. Oil-sardine eggs were not encountered in the collections from SZ. Nevertheless, during phase-1 of SM, sardine larvae were abundant in the 30m (279 larvae), 50m (40445 larvae) & 100m (7789 larvae) isobaths of the SZ (Table 4.4), which implies that they may spawn in the SZ also. This assumption was proved right, in a subsequent cruise (FORV SS- 360 in May 2017) wherein one Bongo full of sardine eggs (83848 eggs.10m^{-2}) was collected from the 50m depth station off Trivandrum (8°21.43'N; 76°51.84'E) on the 25th of May, setting an exception to the general trend observed in the previous years. Considerable spawning activity of oil sardine and presence of oil sardine eggs during May was reported by Lazarus (1985) at Vizhinjam (8.4°N). The total absence of sardine eggs in our collections from SZ during the present study period, may be due to earlier spawning of sardines in the SZ (ie; before phase-1 period of 15 May to 15 June) and that the May 2017 collections from the 50m station may be an aberration from the general trend. Oil sardine eggs were obtained from the CZ during phase-1 of year 2009 (666 egg.10m^{-2}) and phase-3 of years 2009 (108 eggs.10m^{-2}) and 2015 (5871 eggs.10m^{-2}). In the NZ sardine eggs were detected in phase-3 of year 2009 (215 eggs.10m^{-2}) and 2015 (51640 eggs.10m^{-2}). Binu (2003) also observed an oil sardine spawning ground at Kannur (12°N) during SM. George (1989) reported the spawning grounds of oil sardine and

occurrence of larvae from 11°30N to 15°30N with its maximum abundance from April to August and their peak in July.

Though the present data set do not cover shallow coastal waters below 30m isobaths (due to inherent operational limitations of the vessel FORV-SS) where maximum oil-sardine egg abundance is expected, from the available data it appears that oil-sardines in general prefers the onset phase of SM upwelling for peak spawning which appears to be prior to 15 May and the starting of phase-1 SM in the SZ and phase-1 SM (15 May to 14 June) in the CZ and phase-3 SM in the NZ. In the SZ, 0.5% larvae were found in the 30m isobath, 79% in the 50m, 15.3% in the 100, 2.4% in the 200m and 2.8% in the 500m isobaths. For the CZ larval distribution was nil for 30m, 56.4% in the 100m, 21.8% each for the 100m & 200m isobaths and nil in the 500m isobaths. In the NZ 26.4% larvae were in the 30m, 67% in the 50m, 4.9% in the 100m, 1.4% in the 200m and only 0.3% was found in the 500m depth strata. These results are consistent with the strength of offshore transport, details of which are explained in chapter-6.

R.kanagurta eggs were obtained only during phase-1 of year 2009, from the 50m station (975 eggs.10m^{-2}) and the 200m station (255 eggs.10m^{-2}) off Trivandrum (total of 1230 eggs.10m^{-2}) on 2.6.2009. Bongo collections from off Kannur on 11 Jun 2009 from the 50m station (530 eggs.10m^{-2}) and the 100m station (1180 eggs.10m^{-2}) also yielded good quantities (1710 eggs.10m^{-2}) of mackerel eggs. Despite reasonably good sampling efforts, mackerel eggs were not found in the 30m stations throughout the study area, which suggest that the species spawn in the 50m to the 200m isobaths. Similar observations were also made by Oliver (1990) regarding the spawning grounds of Cape horse-mackerel in the northern Benguela region and by Krishnakumar *et al.,* (2008) for the

Indian mackerel from SEAS. SZ accounted for 41.8% of egg and 93.3% of larval abundance and the NZ had 58.6% egg and 6.3% larval abundance during phase-1 of the study period. Mackerel eggs were conspicuously absent in the CZ and the occurrence of larvae was negligible (0.4%) during all the 3 phases of the study period (Table 4.4). This indicates that mackerel avoid CZ for spawning and as nursery grounds.

For the anchovy, *E.devisi* though eggs were obtained only in the phase-1 collections from SZ (435 eggs.10m^{-2}), CZ (98 eggs.10m^{-2}) and NZ (530 eggs.10m^{-2}), their larval distribution is found to be spread across all the 3 zones (40.8% in SZ, 26.9% in CZ and 32.3% in NZ) in all the 3 phases of SM upwelling season, implying that they probably spawn throughout the SEAS during all phases of SM. George (1988) reported the elliptical eggs of *Anchoviella devisi* from November to July from Vizhinjam (8.4^{o}N).

The three coastal pelagic species accounted for nearly 70% of the total larval abundance (72734 nos.10m^{-2}) of SEAS during SM season with oil sardine forming 55.5%, *E.devisi* 7.2% and Indian mackerel 7.05%. Total larval abundance in the 3 zones of SEAS did not show any positive correlation with egg abundance. This suggests that the eggs and larvae are widely dispersed by surface current drifts and/or through turbulence. As expected, the larval abundance showed zonal and phase-wise variations that were in line with the appearance and northward progression of SM upwelling. In phase-1, the SZ accounted for 90.9% of larval abundance (107655 ind.10m^{-2}), followed by the NZ (4.9%) and the CZ (4.2%). During phase-2, the CZ showed 60.8% larval abundance with the SZ & NZ contributing to 20.6% & 18.6% of the total larval abundance (3033

ind.10m^{-2}). Phase-3 of the SM season was marked by high abundance of larvae in the NZ (60.6% of the total of 20249 ind.10m^{-2}) followed by the CZ (23.8%) and SZ (15.6%). Larval abundance decreased from the coast (60.18%) to the shelf (34.46%) and slope (5.36%) areas. High larval abundance in the SZ during Phase-1, in the CZ during phase-2 and in NZ during phase-3 is consistent with the northward progression of SM upwelling.

The general trends in the abundance and distribution of larvae are also reflected in the case of oil sardine larvae. In phase-1 of SM, oil sardine larvae mostly in the flexion stage were obtained exclusively from the SZ with the Kollam and Cape transects dominating in larval abundance. Our larval abundance data for phase-2 is limited to 20 ind.10m^{-2} and is therefore not considered for analysis. Of the 5708 larvae.10m^{-2} recorded from NZ during phase-3 of SM, 63% were from the NZ, 32.6% from the CZ and only 4.4% were from SZ.

From the available data, it is clear that *E.devisi* larvae are most abundant during phase-1 (84.3%) and show relatively low abundance during phase-2 (11.3%) and phase-3 (4.4%). This suggests that peak spawning of the species possibly occur between mid-April and mid-May season. This is corroborated with the finding that *E.devisi* eggs were totally absent in the collections made during phase-2 & phase-3 of SM. The fact that larvae were distributed almost evenly in the 3 zones of the study area during phase-1 viz; the SZ (45.8% abundance), CZ (21.6% abundance) and NZ (32.6% abundance) is an indication that *E.devisi* spawn over a wide range of area, without any strong preference to a particular zone. George (1988) noted that high concentrations of *Anchoviella sp.* larvae were observed at open ocean stations and their larvae were high during

May at Vizhinjam waters (8.4°N). George (1989) reported dense distribution of *Stolephorus sp* from 7°30N to 11°30N and a peak abundance at March to July. *E.devisi* were reported abundant between 15m and 45m bottom depths (Gopakumar and Pillai, 2000). Binu (2003) recorded *E. devisi* larvae from Cochin and Mangalore region. They observed that *E.devisi* larvae were represented throughout the year with a peak abundance during summer monsoon and winter mosoon. Gopakumar and Pillai (2000) noted that at Vizhinjam (SZ), *E.devisi* spawns throughout the year with its peak at March to May, at Cochin during October to June and at Mangalore during September to May. The observed shift in larval abundance from the SZ (45.7%) to the CZ (91.4%) and NZ (67.9%) during phase-1, 2 & 3 of SM season, indicates that spawning and/or larval survival rates are dependent on the strength of SM upwelling.

To conclude, the 3 coastal pelagic species account for nearly 70% of the total fish larval abundance of SEAS for the SM season with oil sardine contributing to as much as 55.5% of the total fish larval abundance (72734 larvae.10m^{-2}), followed by *E.devisi* with a contribution of 7.2% and *R.kanagurta* with a contribution of 7.05%. Although *S.longiceps*, *E.devisi* and *R.kanagurta* occupy the same habitat for spawning and as nursery grounds, subtle variations in spawning grounds, peak spawning period and location of nursery grounds are expected to avoid interspecific competitions amongst these species for food and space. *E.devisi* appears to spawn throughout the study area much earlier (mid-April to mid-May) than the other two species with its spawning and nursery grounds distributed all along the coastal belt of SEAS. On the other hand, peak spawning period in *R.kanagurta* corresponds with the onset phase of SM upwelling (mid-May to mid-June) with major spawning grounds located beyond the 50m isobaths, which help avoid direct competition with *E.*

devisi larvae. In *S.longiceps*, spawning is rather protracted with peak spawning in SZ prior to phase-1, during phase-1 in the CZ and during phase-3 in the NZ with wide larval dispersal which help them reduce competition with the other two species.

Table 4.1. Numerical abundance (Nos.10m^{-2}) of (1&2) total fish eggs and Larvae (3&4) *Sardinella longiceps (5&6) Rastrelliger kanagurta* and (7&8) *Encrasicholina devisi* eggs and larvae in different zones during the 3 phases of SM.

Survey	No. of Bongo Stns	NZ	CZ	SZ	Total	Mean Abd	Range
1. Fish Eggs Nos.10m^{-2}							
Phase-1 of 2009	39	9118	61120	14885	85123	2182.64±6219.92	2 to 32948
Phase-1 of 2010	12	-	-	37712	37712	3142.74±9818.51	7 to 34284
Phase-1 of 2015	25	1842	3160	3582	8596	343.86±502.44	2 to 2150
Phase-2 of 2010	20	1112	7004	13278	21394	1069.73±2223.39	1 to 6956
Phase-3 of 2009	64	4486	3017	15598	152876	2388.67±9668.59	1 to 66401
Phase-3 of 2013	44	6389	224	21	6634	150.77±478.78	1 to 2848
Phase-3 of 2015	30	52674	6808	15120	74602	2487±9611	6 to 51640
2. Fish Larvae Nos.10m^{-2}							
Phase-1 of 2009	39	4861	3767	51551	60179	1543.05± 6841.55	6 to 42933
Phase-1 of 2010	12	-	-	44614	44614	3717.83±7893.14	15 to 24219
Phase-1 of 2015	25	371	786	1705	2862	114.49 ±143.11	3 to 554
Phase-2 of 2010	20	565	1844	624	3033	151.63±210.17	7 to 786
Phase-3 of 2009	64	8227	391	2253	10871	169.86±761.65	1 to 6009
Phase-3 of 2013	44	3348	4262	199	7809	177.49±612.86	1to 3564
Phase-3 of 2015	30	683	174	711	1569	52.29±91.99	2 to 359
3. Sardinella longiceps eggs Nos.10m^{-2}							
Phase-1 of 2009	39	0	666	0	666	17±106.68	0 to 666
Phase-1 of 2010	12	0	0	0	0	0	0
Phase-1 of 2015	25	0	0	0	0	0	0
Phase-2 of 2010	20	0	0	0	0	0	0
Phase-3 of 2009	64	215	108	0	323	5±29.92	0 to 215
Phase-3 of 2013	44	0	0	0	0	0	0
Phase-3 of 2015	30	51640	5871	0	57511	1917±9452.07	0 to 51640
***4. Sardinella longiceps* larvae ind.10m^{-2}**							
Phase-1 of 2009	39	0	0	42948	42948	1101.24±6394.17	0 to 39980
Phase-1 of 2010	12	-	-	23901	23901	1991±4757.04	0 to 15657
Phase-1 of 2015	25	10	0	148	158	6.31±21.35	0 to 100
Phase-2 of 2010	20	9	3	8	19	0.95±2.36	0 to9
Phase-3 of 2009	64	563	23	125	711	11.11±58.06	0 to 454
Phase-3 of 2013	44	3014	1700	0	4714	107.14±379.27	0 to 1833
Phase-3 of 2015	30	19	137	127	283	9.44±26.6	0 to 117

Table 4.1. Numerical abundance (Nos.10m^{-2}) of (1&2) total fish eggs and Larvae (3&4) *Sardinella longiceps (5&6) Rastrelliger kanagurta* and (7&8) *Encrasicholina devisi* eggs and larvae in different zones during the 3 phases of SM. (Contd..)

5. *Rastrelliger kanagurta eggs* ind.10m^{-2}							
Phase-1 of 2009	39	1710	0	1230	2940	75±254.81	0 to 1710
Phase-1 of 2010	12	0	0	0	0	0	0
Phase-1 of 2015	25	0	0	0	0	0	0
Phase-2 of 2010	20	0	0	0	0	0	0
Phase-3 of 2009	64	0	0	0	0	0	0
Phase-3 of 2013	44	0	0	0	0	0	0
Phase-3 of 2015	30	0	0	0	0	0	0
6. *Rastrelliger kanagurta* larvae ind.10m^{-2}							
Phase-1 of 2009	39	386	2	3604	3992	102.35±471.42	0 to 2934
Phase-1 of 2010	12	-	-	445	445	37.06±108.07	0 to 377
Phase-1 of 2015	25	0	0	205	205	8.19±39.91	0 to 199
Phase-2 of 2010	20	27	10	264	301.07	15.05±58.88	0 to 264
Phase-3 of 2009	64	46	23	0	69	1±5.42	0 to 41
Phase-3 of 2013	44	78	26	7	111	2.53±8.39	0 to 52
Phase-3 of 2015	30	2	0	0	2	0.07±0.37	0 to 2
7. *Encrasicholina devisi* eggs ind.10m^{-2}							
Phase-1 of 2009	39	530	0	0	530	0	0
Phase-1 of 2010	12	0	0	0	0	0	0
Phase-1 of 2015	25	0	98	435	533	21.32±88.38	0 to 435
Phase-2 of 2010	20	0	0	0	0	0	0
Phase-3 of 2009	64	0	0	0	0	0	0
Phase-3 of 2013	44	0	0	0	0	0	0
Phase-3 of 2015	30	0	0	0	0	0	0
8. *Encrasicholina devisi* larvae ind.10m^{-2}							
Phase-1 of 2009	39	2406	1382	1932	5720	146.66±346.45	0 to 1711
Phase-1 of 2010	12	-	-	982	982	81.81±233.88	0 to 817
Phase-1 of 2015	25	178	328	714	1220	48.81±120.56	0 to 548
Phase-2 of 2010	20	36	975	56	1067	53.35±125.96	0 to 166
Phase-3 of 2009	64	0	9	0	9	0.1±1.10	0 to 9
Phase-3 of 2013	44	0	40	15	55	1.24±4.87	0 to 30
Phase-3 of 2015	30	285	27	44	356	11.88±47.83	0 to 263

Phase-1: 15 May to 14 June; Phase -2: 15 June to 14 July & Phase-3: 15 July to end SM

Table 4.2. Numerical abundance (nos.10m^{-2}) of (1&2) total fish eggs & larvae (3&4) *Sardinella longiceps* (5&6) *Rastrelliger kanagurta* and (7&8) *Encrasicholina devisi* egg & larvae in the coastal, shelf and slope stations of the three zones during different phases of monsoon.

Survey	NZ			CZ			SZ		
	Coastal	Shelf	Slope	Coastal	Shelf	Slope	Coastal	Shelf	Slope
1. Fish Eggs nos.10m^{-2}									
Phase-1 of 2009	729	7837	-	55192	4839	1089	8132	4797	1956
Phase-1 of 2010	-	-	-	-	-	-	2652	34992	68
Phase-1 of 2015	29	1770	44	749	2370	40	892	2216	475
Phase-2 of 2010	461	652	-	6632	299	81	6322	6956	-
Phase-3 of 2009	2163	2322	1	2153	863	2	111067	33309	994
Phase-3 of 2013	5019	553	817	199	25	-	11	1	9
Phase-3 of 2015	51736	301	638	5981	487	339	1952	214	12948
2. Fish Larvae nos.10m^{-2}									
Phase-1 of 2009	128	4733	-	1365	825	1578	44709	2977	3865
Phase-1 of 2010	-	-	-	-	-	-	18799	25456	359
Phase-1 of 2015	296	25	51	382	157	248	586	961	158
Phase-2 of 2010	122	443	-	1166	300	376	61	562	-
Phase-3 of 2009	2109	6043	49	362	28	1	927	1200	126
Phase-3 of 2013	3208	95	46	4017	245	-	40	38	122
Phase-3 of 2015	35	403	246	86	35	54	155	112	445
3. *Sardinella longiceps eggs* nos.10m^{-2}									
Phase-1 of 2009	0	0	0	666	0	0	0	0	0
Phase-1 of 2010	-	-	-	-	-	-	0	0	0
Phase-1 of 2015	0	0	0	0	0	0	0	0	0
Phase-2 of 2010	0	0	0	0	0	0	0	0	0
Phase-3 of 2009	215	0	0	108	0	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	0	0	0	0
Phase-3 of 2015	51640	0	0	5871	0	0	0	0	0
4. *Sardinella longiceps larvae* nos.10m^{-2}									
Phase-1 of 2009	0	0	-	0	0	0	6	41613	1330
Phase-1 of 2010	-	-	-	-	-	-	196	23589	117
Phase-1 of 2015	10	0	0	0	0	0	106	1	0
Phase-2 of 2010	9	0	-	3	0	0	1	6	-
Phase-3 of 2009	563	0	0	23	0	0	90	35	0
Phase-3 of 2013	3013	0	1	1654	47	-	0	0	0
Phase-3 of 2015	19	0	0	0	54	83	117	0	9

Table 4.2. Numerical abundance (nos.10m^{-2}) of (1&2) total fish eggs & larvae (3&4) *Sardinella longiceps* (5&6) *Rastrelliger kanagurta* and (7 & 8) *Encrasicholina devisi* egg & larvae in the coastal, shelf and slope stations of the three zones during different phases of monsoon. (Contd..)

5. *Rastrelliger kanagurta eggs* nos.10m^{-2}									
Phase-1 of 2009	1710	0	0	0	0	0	1230		
Phase-1 of 2010	-	-	-	-	-	-	0	0	0
Phase-1 of 2015	0	0	0	0	0	0	0	0	0
Phase-2 of 2010	0	0	0	0	0	0	0	0	0
Phase-3 of 2009	0	0	0	0	0	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	0	0	0	0
6. *Rastrelliger kanagurta larvae* nos.10m^{-2}									
Phase-1 of 2009	0	386	-	2	0	0	3216	276	112
Phase-1 of 2010	-	-	-	-	-	-	23	421	0
Phase-1 of 2015	0	0	0	0	0	0	200	5	0
Phase-2 of 2010	27	0	-	0	10	0	0	264	-
Phase-3 of 2009	46	0	-	11	12	-	0	0	0
Phase-3 of 2013	68	10	0	0	26	-	0	1	7
Phase-3 of 2015	0	2	0	0	0	0	0	0	0
7. *Encrasicholina devisi eggs* nos.10m^{-2}									
Phase-1 of 2009	0	0	0	0	0	0	0	0	0
Phase-1 of 2010	-	-	-	-	-	-	0	0	0
Phase-1 of 2015	0	0	0	98	0	0	435	0	0
Phase-2 of 2010	0	0	0	0	0	0	0	0	0
Phase-3 of 2009	0	0	0	0	0	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	0	0	0	0
8. *Encrasicholina devisi larvae* nos.10m^{-2}									
Phase-1 of 2009	22	2384	-	1131	217	34	338	472	1122
Phase-1 of 2010	-	-	-	-	-	-	36	928	17
Phase-1 of 2015	178	0	0	271	58	0	28	673	13
Phase-2 of 2010	29	6	-	853	107	15	3	54	-
Phase-3 of 2009	0	0	-	0	9	-	0	0	0
Phase-3 of 2013	0	0	0	0	40	-	0	6	9
Phase-3 of 2015	5	278	2	9	4	15	36	0	7

Coastal <50 m isobath; Shelf 50m to 200m isobaths; Slope > 200 m isobath.

Table 4.3 Numerical abundance (Nos.10m^{-2}) of (1&2&3) *Sardinella longiceps* (4&5&6) *Rastrelliger kanagurta* and (7&8&9) *Encrasicholina devisi* preflexion, flexion and postflexion stages in coastal, shelf and oceanic stations of the different zones during the 3 phases of monsoon

Survey	NZ				CZ				SZ			
	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total
***1. Sardinella longiceps*- Preflexion stages (nos.10m^{-2})**												
Phase-1 of 2009	0	0	0	0	0	0	0	0	6	5806	618	6430
Phase-1 of 2010	-	-	-	-	-	-	-	-	0	26	0	26
Phase-1 of 2015	0	0	0	0	0	0	0	0	46	1	0	4
Phase-2 of 2010	3	0	-	3	0	0	0	0	0	0	-	0
Phase-3 of 2009	10	150	-	160	0	23	-	23	0	20	0	20
Phase-3 of 2013	21	0	0	21	1327	0	-	1327	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	0	0	0	0	0	0	0
***2. Sardinella longiceps*- Flexion stages (nos.10m^{-2})**												
Phase-1 of 2009	0	0	0	0	0	0	0	0	0	27521	712	28232
Phase-1 of 2010	-	-	-	-	-	-	-	-	29	13897	6	13931
Phase-1 of 2015	0	5	0	5	0	0	0	0	60	19	0	22
Phase-2 of 2010	5	0	-	5	0	0	0	0	1	5	-	7
Phase-3 of 2009	62	316	-	378	0	0	-	0	0	40	0	40
Phase-3 of 2013	931	1842	0	2773	102	181	-	283	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	29	93	123	0	117	0	117

Survey	NZ				CZ				SZ			
	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total
***3. Sardinella longiceps* – Postflexionstages (nos.10m^{-2})**												
Phase-1 of 2009	0	0	0	0	0	0	0	0	0	8286	0	8286
Phase-1 of 2010	-	-	-	-	-	-	-	-	167	9666	111	9944
Phase-1 of 2015	0	5	0	5	0	0	0	0	0	22	0	22
Phase-2 of 2010	0	0	-	0	0	2	0	2	0	1	-	1
Phase-3 of 2009	17	8	-	25	0	0	-	0	0	65	0	65
Phase-3 of 2013	201	19	0	220	4	87	-	91	0	0	0	0
Phase-3 of 2015	0	19	0	19	0	15	0	15	0	9	0	9
***4. Rastrelliger kanagurta*- Preflexion stages (nos.10m^{-2})**												
Phase-1 of 2009	0	28	-	28	0	0	0	0	0	1067	75	1142
Phase-1 of 2010	-	-	-	-	-	-	-	-	0	6	0	6
Phase-1 of 2015	0	0	0	0	0	0	0	0	0	3	0	3
Phase-2 of 2010	0	9	-	9	0	0	0	0	0	8	-	8
Phase-3 of 2009	0	7	-	7	0	12	-	12	0	0	0	0
Phase-3 of 2013	6	12	0	18	0	6	-	6	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	0	0	0	0	0	0	0

Survey	NZ				CZ				SZ			
	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total
***5. Rastrelliger kanagurta*- Flexion stages (nos.10m^{-2})**												
Phase-1 of 2009	0	360	-	360	0	1	0	1	0	1772	37	1809
Phase-1 of 2010	-	-	-	-	-	-	-	-	0	162	0	162
Phase-1 of 2015	0	0	0	0	0	0	0	0	0	174	3	177
Phase-2 of 2010	0	18	-	18	0	10	0	10	0	215	-	215
Phase-3 of 2009	4	28	-	32	0	8	-	8	0	0	0	0
Phase-3 of 2013	44	11	0	55	0	0	-	0	0	0	0	0
Phase-3 of 2015	0	2	0	2	0	0	0	0	0	0	0	0
***6. Rastrelliger kanagurta* – Postflexionstages (nos.10 m^{-2})**												
Phase-1 of 2009	0	0	-	0	0	1	0	1	0	653	0	653
Phase-1 of 2010	-	-	-	-	-	-	-	-	23	252	0	275
Phase-1 of 2015	0	0	0	0	0	0	0	0	0	25	0	25
Phase-2 of 2010	0	0	-	0	0	0	0	0	0	42	-	42
Phase-3 of 2009	1	5	-	6	0	3	-	3	0	0	0	0
Phase-3 of 2013	3	2	0	5	0	21	-	21	0	1	6	7
Phase-3 of 2015	0	0	0	0	0	0	0	0	0	0	0	0

Survey	NZ				CZ				SZ			
	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total
***7. Encrasicholina devisi*- Preflexion stages (nos.10m^{-2})**												
Phase-1 of 2009	2	0	-	2	3	433	0	436	7	151	114	272
Phase-1 of 2010	-	-	-	-	-	-	-	-	0	0	0	0
Phase-1 of 2015	0	0	0	0	0	15	0	15	9	0	196	205
Phase-2 of 2010	0	1	-	1	47	12	0	59	0	0	-	0
Phase-3 of 2009	0	0	0	0	0	3	-	3	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	0	-	0	0	0	0	0
Phase-3 of 2015	0	0	0	0	0	2	0	2	0	0	8	8
***8. Encrasicholina devisi*- Flexion stages (nos.10m^{-2})**												
Phase-1 of 2009	0	1297	-	1297	0	435	34	469	0	407	866	1272
Phase-1 of 2010	-	-	-	-	-	-	-	-	0	234	3	237
Phase-1 of 2015	13	76	0	89	3	197	0	200	19	7	296	323
Phase-2 of 2010	0	10	-	10	267	126	0	393	0	12	-	12
Phase-3 of 2009	0	0	0	0	0	6	-	6	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	9	-	9	0	1	0	1
Phase-3 of 2015	0	2	11	13	0	8	0	8	33	3	0	36

Survey	NZ				CZ				SZ			
	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total	Coastal	Shelf	Slope	Total
9. Encrasicholina devisi – Postflexionstages (nos.10m^{-2})												
Phase-1 of 2009	0	863	-	863	0	391	0	391	0	186	142	328
Phase-1 of 2010	-	-	-	-	-	-	-	-	7	723	14	745
Phase-1 of 2015	13	76	0	89	2	109	2	114	0	30	158	189
Phase-2 of 2010	0	25	-	25	271	243	9	523	0	43	-	43
Phase-3 of 2009	0	0	0	0	0	0	-	0	0	0	0	0
Phase-3 of 2013	0	0	0	0	0	31	-	31	0	6	8	14
Phase-3 of 2015	0	18	254	272	0	2	15	17	0	0	0	0

Table 4.4 Depth/Season/Zone wise distribution of Eggs & Larvae (no.10m^{-2}).

Phase of SM	Zone	Eggs			Larvae		
30 m		**S**	**M**	**A**	**S**	**M**	**A**
Phase-1	SZ	0	0	435	279	23	50
	CZ	666	0	98	0	0	8
	NZ	0	0	0	0	0	2
Phase-2	SZ	0	0	0	1	0	0
	CZ	0	0	0	0	0	568
	NZ	0	0	0	98	5	0
Phase-3	SZ	0	0	0	0	0	0
	CZ	5979	0	0	0	0	0
	NZ	51855	0	0	89	5	0
50 m							
Phase-1	SZ	0	975	0	40445	6902	313
	CZ	0	0	0	0	2	1022
	NZ	0	530	530	0	0	20
Phase-2	SZ	0	0	0	0	0	3
	CZ	0	0	0	3	0	268
	NZ	0	0	0	0	27	30
Phase-3	SZ	0	0	0	90	0	0
	CZ	0	0	0	23	9	0
	NZ	0	0	0	474	81	0
100 m							
Phase-1	SZ	0	0	0	7789	443	1014
	CZ	0	0	0	0	0	95
	NZ	0	1180	0	0	0	584
Phase-2	SZ	0	0	0	7	265	52
	CZ	0	0	0	0	0	72

S,*S.longiceps*: M, *R.kanagurta*: A, *E.devisi*

Table 4.4 Depth/Season/Zone wise distribution of Eggs & Larvae. (Contd..)

Phase of SM	Zone	Eggs			Larvae		
		S	M	A	S	M	A
Phase-2	NZ	0	0	0	0	0	5
Phase-3	SZ	0	0	0	3	0	8
	CZ	0	0	0	10	14	10
	NZ	0	0	0	35	0	263
200 m							
Phase-1	SZ	0	255	0	1250	259	904
	CZ	0	0	0	0	0	181
	NZ	0	0	0	0	416	1557
Phase-2	NZ	0	0	0	0	0	15
	CZ	0	0	0	0	0	0
	NZ	0	0	0	0	10	263
Phase-3	NZ	0	0	0	0	7	17
	CZ	0	0	0	10	12	11
	NZ	0	0	0	2	0	263
500 m							
Phase-1	SZ	0	0	0	121	0	1075
	CZ	0	0	0	0	0	28
	NZ	0	0	0	0	0	0
1000 m							
Phase-1	SZ	0	0	0	0	0	13
	CZ	0	0	0	0	0	0
	NZ	0	0	0	0	0	0
Phase-2	SZ	0	0	0	0	0	0
	CZ	0	0	0	0	0	15
	NZ	0	0	0	0	0	0
Phase-3	SZ	0	0	0	7	0	9
	CZ	0	0	0	0	0	15
	NZ	0	0	0	0	0	2

S,*S.longiceps*: M, *R.kanagurta*: A, *E.devisi*

Chapter 5

Correlating Larval abundance with Environment and Productivity Patterns

5.1. *Introduction*

Stock size of pelagic fish are strongly linked to the environmental characteristics especially during their early life history stages. The survival of first feeding larvae is greatly dependent on the environmental conditions, food availability and vulnerability to predators (Ramzi *et al.,* 2006). Fish larvae are most susceptible during the transition from yolk-sac stage to the planktivorous stage (Lasker, 1975). The environment plays an important role in the dynamics of pelagic fish of the world's upwelling areas (Roy *et al.,* 1992). In the upwelling areas, most of the larval mortality is related to offshore advection and early stage mortality (Brochier *et al.,* 2008b; Bakun, 1996). Therefore a clear understanding of the early developmental stages is critical in explaining the observed oscillations in fishery and also in predicting their response strategies to climate change. Such studies can contribute substantially to the proper management of fishery resources. While the influence of seasonal upwelling on the holoplankton has been well explained, the distribution of ichthyoplankton and other meroplanktons such as crustacean larvae has received only limited attention so far. Cushing (1969) described that

variations in the recruitment can be explained by the match and mismatch hypothesis. If the breeding of the higher level predator occurs during the peak availability of the prey, then the recruitment will be high. The growth and survival of fish larvae depend solely on external food resources after the absorption of the yolk. The survival rate of the larvae and thus the recruitment can be low in the absence of prey. Thus the prevailing environment has an indirect effect on the recruitment success, by affecting the timing of food requirement and the availability of the food.

Pioneer studies on spawning seasons of oil sardine were carried out by Hornell and Naidu (1924), followed by Devanesan (1943). Spawning biology of oil sardine was examined by Antony Raja, 1964. According to him spawning season extends from July to September and occasionally to October. Seasonal changes in the ovary weight shows that the maturation starts in May, increases its activity in June –July and reaches its peak during August. Studies on ova diameter of oil sardine reveal that eggs are released in a number of batches. Active spawning of oil sardine along Mangalore coast was from June to September (Dhulkhed 1968) and 3 to 4 batches of eggs are released in a season (Dhulkhed, 1964). At Karwar the oil sardine spawning season is from July to August and from November to December (Annigeri, 1969). From these studies the major spawning period of oil sardine along the west coast appears to be from June to August. Antony Raja, 1970, highlighted that larvae hatched from June to August are the major contributors to the next year fishery while September and October born fails to represent as they are low in number. In another study, Antony Raja, 1966, reported the occurrence of vascular heterotrophy and follicular breakdown in advanced stages of ovaries during July to August. Balan 1972, reported the spawning from June to August and Bensam 1970, observed spawning

from April to August at Kannur. George 1989, observed that along west coast, sardine larvae were abundant during April to August and the peak was during July.

Previous studies have recorded that Indian mackerel has a prolonged spawning period. Sekharan (1958) observed that spawning of Indian mackerel starts in April along north of Mangalore and the mackerel eggs are released in batches. Pradhan (1956) observed the spawning of Indian mackerel from June to September. Based on detailed study of intraovarian eggs in Indian mackerel at Mangalore, Rao (1967) concluded that ova are shed in 3 batches. He observed that the first batch was fully ripened while the developments of the second and third batches were arrested at stage IV. Advanced stages of mackerel were found in large numbers during May to October. Radhakrishnan (1962) observed prolonged duration of shedding of ova in batches commencing from June-July at Karwar. Maximum diameter of intraovarian egg of mackerel at Karwar was 0.935mm. Yohannan and Abdurahiman (1998) suggested continuous oogenesis for Indian mackerel consisting of more than 6 batches of ova. He observed the peak spawning during April to July. Studies on reproductive biology by Hulkoti *et al.,* 2013 along the Mangalore region revealed that Indian mackerel spawn only once in a season, but for a prolonged period. Spawning occurred during June to November with its peak during July to August. According to Bhendarkar *et al*., 2013, intense spawning activity occurred during April with a small peak during October and November off Ratnagiri. Yohannan and Nair (2002) reported the main spawning season from May to July along SEAS. Ganga (2010), reported the main spawning period from May to June and a minor peak in November.

Luther, (1979) reported that, intense spawning activity of *Stolephorus devisi* was *during* December to March. Syda Rao, 1988 noted that *S. devisi* attains first maturity at 62 mm length on reaching 3.7 months of age. *S. devisi* releases batches of ova at frequent intervals in the spawning season. George (1988), reported spawning in *S.devisi* during November to July. Gopakumar and Pillai (2000) noted that peak spawning of *E. devisi* along Vizhinjam is during March to May and November to December. At Cochin, peak spawning is in October, March and May and at Mangalore during November, February and May. *E.devisi* spawns throughout the year along Kerala coast with peaks during January to May and September to November.

5.2. *Results*

Figures 5.1 to 5.4 (a to g) depicts the environmental set up in SEAS during different phases of the SM and Table 5.1 provide details on the monthly averages of environmental variables and productivity associated with SM upwelling in SEAS.

5.2.1 *Environmental set up during Phase-1 of SM (Mid-May to Mid-June)*

Met-Ocean conditions play significant roles in the transport and survival of fish eggs and larvae and subsequent recruitment to the fishery. The dominant oceanographic process prevailing in the study area during SM is coastal upwelling. Starting from May, signatures of coastal upwelling such as fall in SST and MLD, increase in productivity and SSS are initiated in the South Zone (SZ) of the study area. The Upwelling phenomenon recorded along the study area gradually extends northward as the season progresses.

During the Phase-1 of SM 2015, SST varied between 27.8 and 31.3°C along the study area (Fig- 5.1a). In the SZ, the coastal SSTs recorded were 27.83°C at T_1 (30m) and 28.09 °C at T_2 (30m) stations. At the 30m and 50m stations off Cape, vertical water column was relatively cooler with temperatures ranging between 27.83°C to 27.14°C and 27.94°C to 25.29°C. The D-24 isotherm was at 45m depth at Cape 100 m station. The distribution of sea surface density indicates the presence of dense water along the coastal waters of off Cape (22.46 Kgm^{-3}) and Trivandrum (22.04 Kgm^{-3}) (Fig. 5.4a). The average magnitude of wind speed in the SZ, CZ and NZ were 6 ms^{-1}, 6 ms^{-1} and 4 ms^{-1} respectively. The SST along in the CZ and NZs varied from 30.71°C at T_5 (200m) to 31.36°C at Calicut 100m indicating the persistence of spring intermonsoon characteristics. The relatively low SST along the coastal waters off Cape and Trivandrum indicates initiation of upwelling at the southern transects. The distribution of dissolved oxygen in the surface waters along the study region varied between 2.86 – 4.67 ml/L with an average of 4.32±0.44 ml/L (Fig.5.3a).

The monsoon set in over Kerala on 23rd May in 2009, one week before its normal date of 1st June. After a hiatus of about 1 week the monsoon further advanced along the west coast up to around 17°N latitude by 7th June. From 8th to 20th June, there was another prolonged hiatus in the advance of the monsoon. The rainfall over the South Peninsula (96% of LPA) was normal (IMD end of-season report 2009). The coastal SSTs were lowered up to 24.83°C, 27.36°C and 27.25°C respectively at the three transects (T_1, T_2 and T_3) of SZ (5.1b). The D24 isotherm was at 12m at Cape 30m and at 32m depth at the 50m station. The surface salinity varied between 34.89psu (T_1, 100) to 35.56psu (T_3, 500m). Dense upwelled waters were present at Trivandrum (T_2)

(23.39Kgm^{-3}) and Cape (23.38 Kgm^{-3}) nearshore stations. The average surface DO of the SZ during late May to mid-June was 4.77 ±0.94ml/L. The average magnitude of the wind speed was 4 ms^{-1} in the SZ. The signatures of coastal upwelling were recorded only in the southern part of the study area during May. The upwelling process was at its initial stage and were observed off Cape, the southern tip of India (8°N; 77.5°E), off Trivandrum and off Kollam up to 50m where it was confined to near shore waters. A coastal upwelling front was identified at Kollam with temperature gradient of 1.457°C for a distance of 31km between 50m station and 100m station with a surface salinity variation of 0.2. Another front associated with upwelling was observed between Cape 30m and Cape 50m station, showing a temperature difference of 1.38°C and density variation of 0.44 Kgm^{-3} within a distance of 12.8Km. In addition to the upwelling fronts, a small meso scale cold core eddy was recognised in satellite imagery at Kollam, Trivandrum region during first week of June (Fig. 5.5). In general, unlike other years signatures of upwelling in the SZ were weak except for the coastal and eddy areas. Beyond the 100m isobaths, non- upwelling conditions prevailed with SSTs off Kollam 100 m as high as 29.21°C. Further northwards, in the CZ the coastal SSTs were higher, 28.47°C (T_5, 30m), 28.75°C (T_6, 30m) and 29.18°C (T_7, 30m). Surface salinity ranged from 34.41psu to 35.55psu (5.2b). The density of the water ranged from 21.75 Kgm^{-3} at T_5 50m to 22.35 Kgm^{-3} at T_7, 100m. In the NZ, the SST was higher and it varied between 28.57°C at (T_8, 30m) to 29.57°C. Densities varied between 21.78 Kgm^{-3} (T_9, 30m) to 22.58 Kgm^{-3} (T_8, 30m) (5.4b). Salinity of 34.47psu was recorded at (T_9, 30m) and 35.72 (T_9, 200m). The average magnitude of wind speed in the central and NZ was 4 ms^{-1} and 3 ms^{-1} respectively. North of Cochin,

upwelling was not evident in the surface waters, but an up sloping of isotherms was recorded in the subsurface layers.

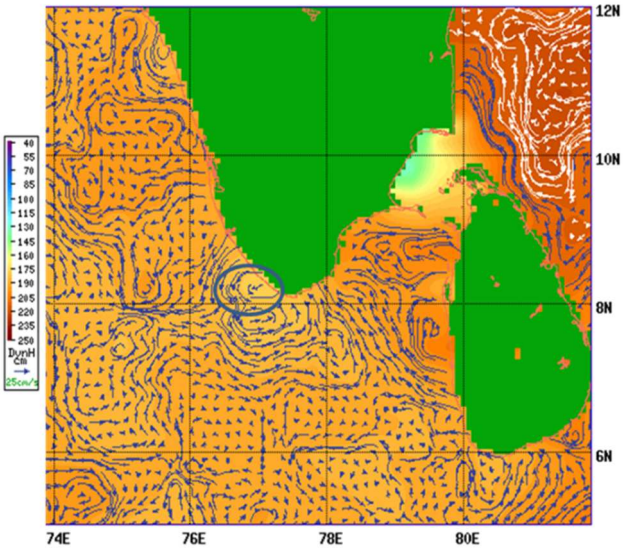


Figure 5.5 Meso-scale cole core eddy in South Zone during phase-1 SM2009

In phase-1 of 2010, coastal SSTs were lowered up to 25.92°C at Cape and 25.22°C at Trivandrum (5.1c). The D 24 isotherm was at 44m depth at Cape 50m station and at 13m depth at Trivandrum 30 m. However, the Cape 30m consisted of an entire warm water column with temperatures varying between 25.87°C to 25.40°C. Dense upwelled waters (23.18°C) and low surface dissolved oxygen waters (2.89 ml/L) (5.3c) occupied the coastal surface waters off Trivandrum. The salinity of the surface waters varied between 34.27psu (T_2, 30) and 35.23psu (T_2, 500) (5.2c). In this phase, the upwelling process was at its initial stage and was present along the two southern transects, Cape and Trivandrum. Upwelling fronts were observed between Cape 30m and 50m coastal stations where a temperature gradient of 1.96°C was recorded. The

density and salinity differences were 0.64 Kgm^{-3} and 0.02psu. Distance between the coastal stations was 20.4Km. Similar fronts associated with upwelling were also observed at Trivandrum coastal (50m) and shelf stations (100m) within a distance of 31Km. Variations in SST, SSS and density between the stations were observed to be 1.48ºC, 0.14psu and 0.35 Kgm^{-3} (Figs 5.1c to 5.4 c).

5.2.2 *Environmental set up during Phase-2 of SM (Mid-June to Mid-July).*

Samples were collected from Kollam to Mangalore from 12 stations during June and July 2010. At the T_3 transect (Kollam) coastal SSTs were lower (26.23ºC), surface waters were more dense (22.43 Kgm^{-3} to 23.67 Kgm^{-3}), SSS varied from 34.3psu (30m) to 34.92psu (100m) and the D 24 isotherm was at 23m depth at the 30m station. The average magnitude of the wind speed of the SZ was 3ms^{-1}. Signatures of upwelling were present at Kollam transect. At the Kochi transect the upsloping waters were still deep showing an elevated SST of 28.60ºC. The D 24 isotherm was at 24m depth at Kochi coastal station. The SST further increased towards north of Cochin. The temperature of the CZ and NZ varied from 28.07ºC (T_8, 50m) to 28.83ºC (T_5, 1000m), density of surface water varied between 21.09 Kgm^{-3} (T_7, 30m) and 22.55 Kgm^{-3}(T_5 30m) and the SSS ranged from 33.60psu (T_7, 100m) to 35.44psu (T_5, 200m). The average magnitude of the wind speed in the CZ was 4ms^{-1} and that of NZ was 4ms^{-1}. Variations in SST, SSS, S-DO and density between the stations is given in figures 5.1d to 5.4d.

5.2.3 *Environmental set up during Phase-3 of SM (Mid-July to end of SM)*

During phase-3 of 2009 survey (FORV SS 270- August 2009), the sampling were carried out at 29 stations, along 7 transects from Cape to Mangalore. SST was low in the SZ and CZ ranging from 23.05°C (T_2, 30m) to 28.56°C (T_7, 100m) (5.1e). Denser waters were observed in these zones showing a mean density of 22.84 ± 0.96 Kgm^{-3} (5.4e). At Kannur coastal station, the observed SST was the lowest (23.80°C). Signatures of upwelling persisted along the southern transects and reached up to Kannur 30m depth station. Further north of Kannur, in the northern transects, the SST increased and it ranged between 28.2°C (T_9, 30m) to 28.39°C (T_9, 200m). Low saline waters were present at Kannur (31.71psu) and Mangalore (32.60psu) coastal waters possibly due to the presence of river plumes at these areas. The thermal structure at the coastal front off Kannur indicated a strong temperature gradient of 4.29ºC between 30m and 50m stations located 18 Km apart. Strong gradients were evident in salinity and density as well. Salinity varied from 34.4psu to 31.7psu and a strong density variation of 3.51 Kgm^{-3} was observed. The average DO was low 3.57±0.91 ml/L along the entire study area. The average magnitude of wind speed in the entire study area was 5±1.52 ms^{-1}. Variations in SST, SSS, S-DO and density between the stations is given in figures 5.1(e) to 5.4(e).

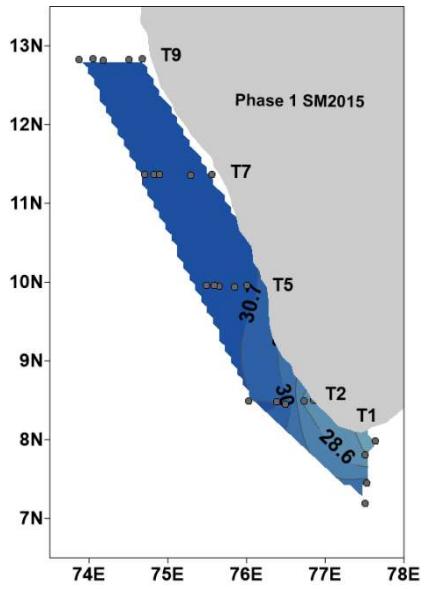
During the end of SM (phase-3 - September 2009), 35 stations were covered along 7 transects from Cape to Mangalore. The SST was low in the entire coast ranging from 24.52ºC (T8, 30m) to 28.96ºC (T_7, 100m). The average surface DO concentration for the entire survey period was low 3.44ml/L± 0.83. Signatures of upwelling were present along the

entire coast. At Mangalore 30m, the D-24 isotherm was at 8m depth. At off Mangalore a low saline plume was recorded in the surface waters which varied from 33.08psu to 32.32psu between 74.67 - 74.47°N (22km). This low saline plume in the region was the indication of intrusion of river water. The thermal gradient 2.17°C recorded in the region was not due to the manifestation of upwelling. Here the surface density varied from 21.9 Kgm^{-3} to 20.69 Kgm^{-3}.

During phase-3, SM 2013, the SST of the entire study area were lower, varying from 23.59°C (T_9, 30m) to 27.83°C (T_{10}, 65m) (5.1f). The density of the water varied from 19.78 Kgm^{-3} (T_8, 200m) to 23.55 Kgm^{-3} (T_{11}, 1000m) (5.4 f)). At Goa 50m station, the D 24 isotherm was at 14m. Here the SSTs varied between 25.78°C to 26.09°C. Signatures of upwelling extended up to Goa. The average surface DO along the entire south west coast was 4.02 ± 0.639 ml/L. Low saline waters were present off Alleppey, Kochi, Kannur and Goa (33.7psu to 31.2psu) (5.2 f). River water intrusion was observed at the coastal and shelf stations off Alleppey transect (33.773psu, 32.102psu, 33.379psu and 33.178psu). The influence of river water extended up to bottom waters of coastal and 100m stations, while at the 200m station its influence was limited up to 140m. Strong river water intrusion was also observed at Goa coastal stations (30m and 50m) up to 8m and 13m depths. Low saline waters were observed in Kochi transect from 30m to 200m depth stations. At Kochi 30m, 50m and 100m stations the influence of river water was observed up to bottom while at the 200m depth station it was present up to 142m. At Valappad transect, at 30m, 50m and 100m stations, the river water was present up to bottom, while at 200m it was present up to 170m. At Calicut transect,

the low saline waters were present at the surface waters off 30m and 50m coastal stations (32.335psu and 32.263psu). The riverine influence was present in the coastal stations up to 9m and 10m. At Kannur shelf stations 50m, 100m and 200m, river water intrusion was observed (31.711psu, 32.212psu and 31.225psu respectively) in the surface waters and it reached up to 8m, 19m and 14m respectively. River water intrusion was present at Mangalore offshore (T_9, 1000m – 33.973psu and T_9, 200m – 34.227psu) stations up to 11m. At Karwar the 30 m and 50m stations had low saline waters at the surface (34.577psu and 33.656psu) extending to 7m at 30m station and 10m at 50m station. Variations in SST, SSS, S-DO and density between the stations is given in figures 5.1 f to 5.4 f.

In phase-3 SM, 2015, SST varied between 22.5°C and 28.5°C along the study area. SST was lower at coastal stations off Calicut (22.68°C), Off Kochi (24.44°C) and off Trivandrum (23.11°C) (5.1g). Denser waters were present in these stations 24.03 Kgm^{-3}, 23.33 Kgm^{-3} and 23.86 Kgm^{-3} respectively (5.4g). At Goa 30m the entire water column was warm. At Goa 50m, the D-24 isotherm was at 33m. Low saline waters were present at Calicut 50m (33.74psu) and Mangalore 30m (32.83psu) (5.2g).


13N
12N
11N
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9N
8N
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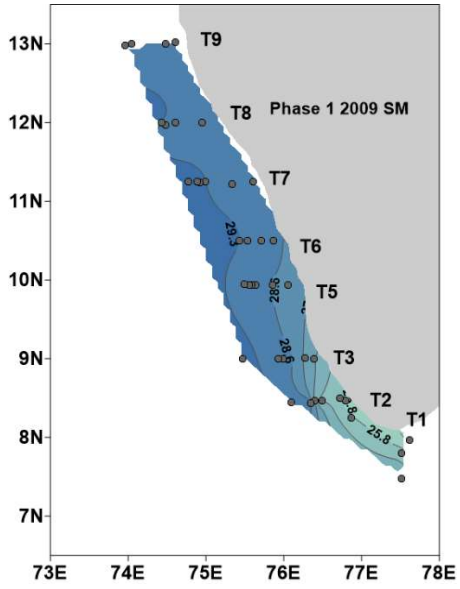
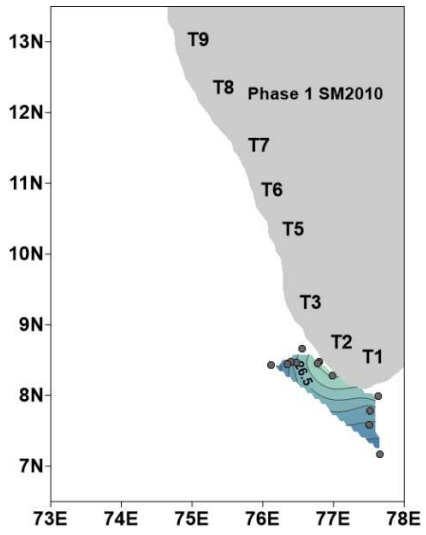
74E
75E
76E
77E
78E
T9
T7
T5
T2
T1
Phase 1 SM2015
30.7
30
28.6

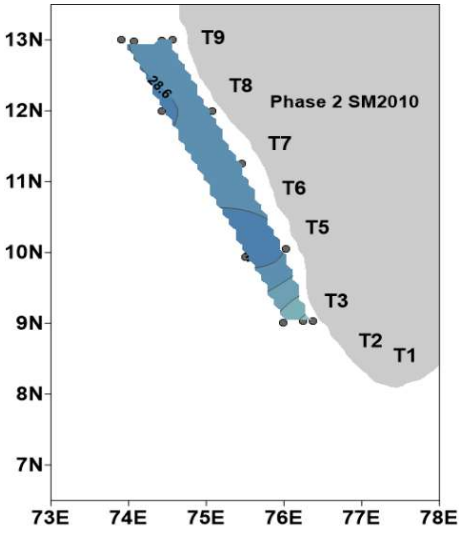
(a)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 2009 SM
28.6
28.8
25.8

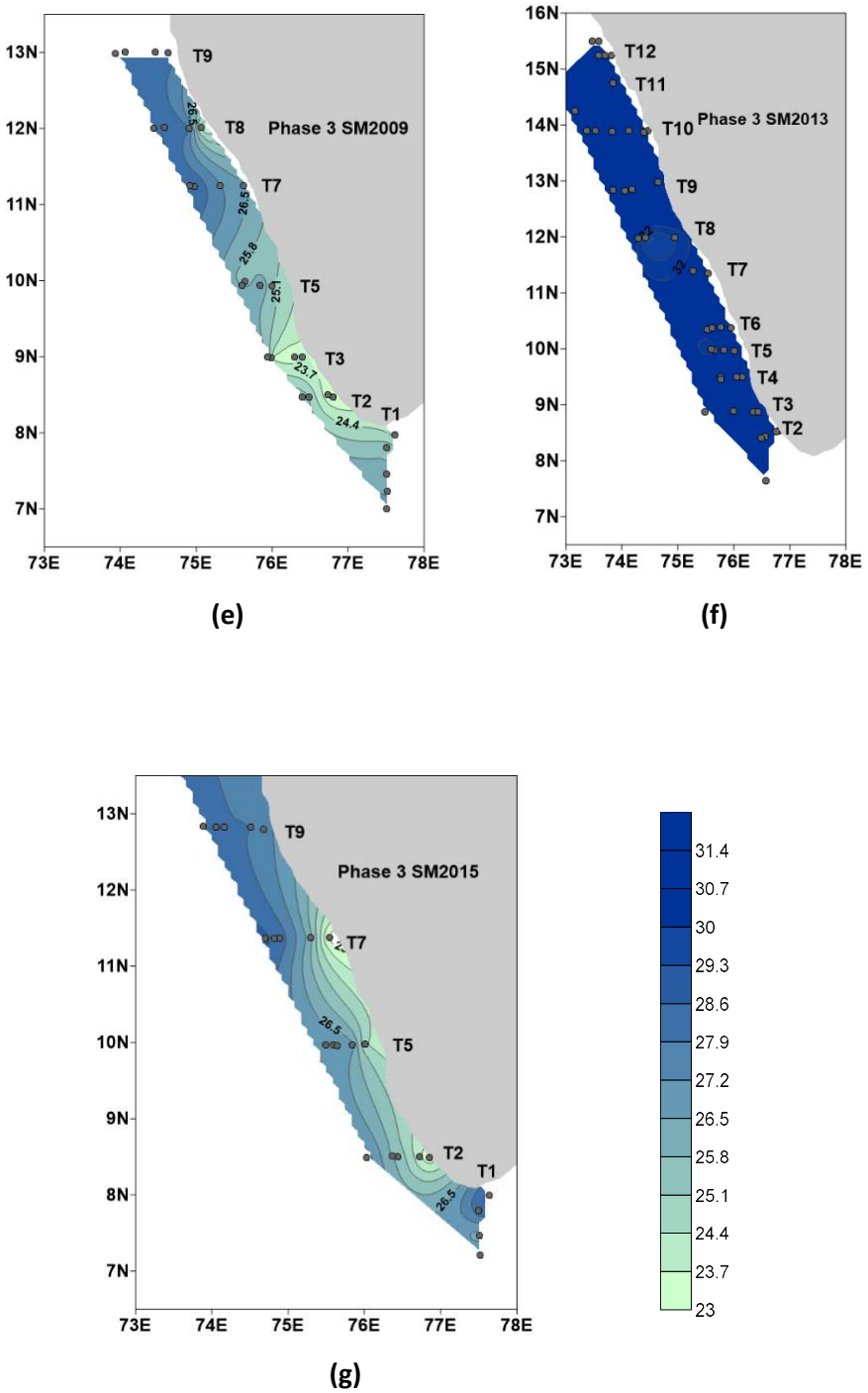
(b)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 SM2010
26.5

(c)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 2 SM2010
28.6

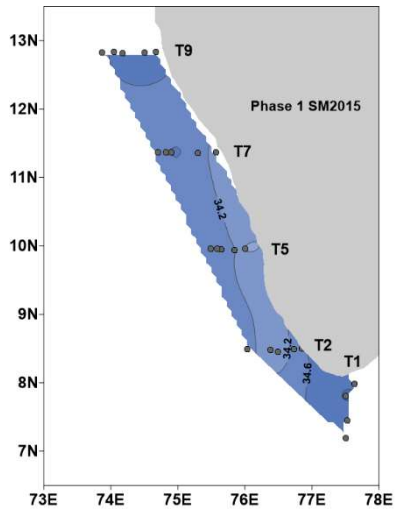
(d)



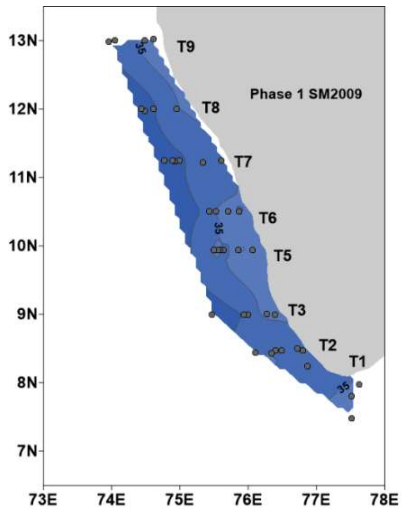
(e) **(f)**

(g)

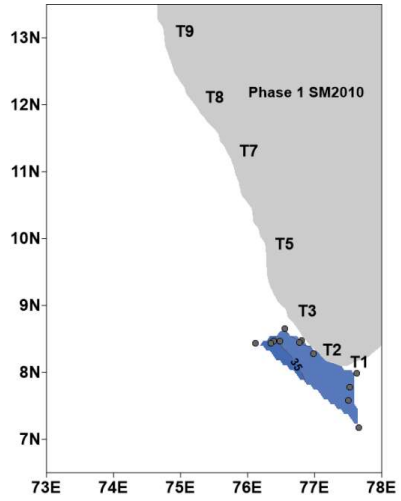
Fig.5.1. Variation in SST during Phase-1 SM2015 (a), Phase-1 SM2009 (b), Phase-1 2010 (c), Phase-2 2010 (d), Phase-3 2009 (e), Phase-3 2013 (f), and Phase-3 2015 (g)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 SM2015
34.2
34.6

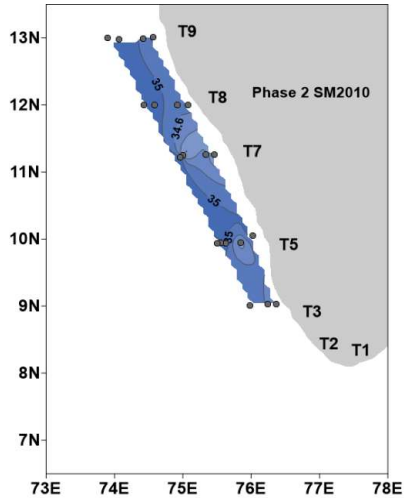
(a)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 SM2009
35

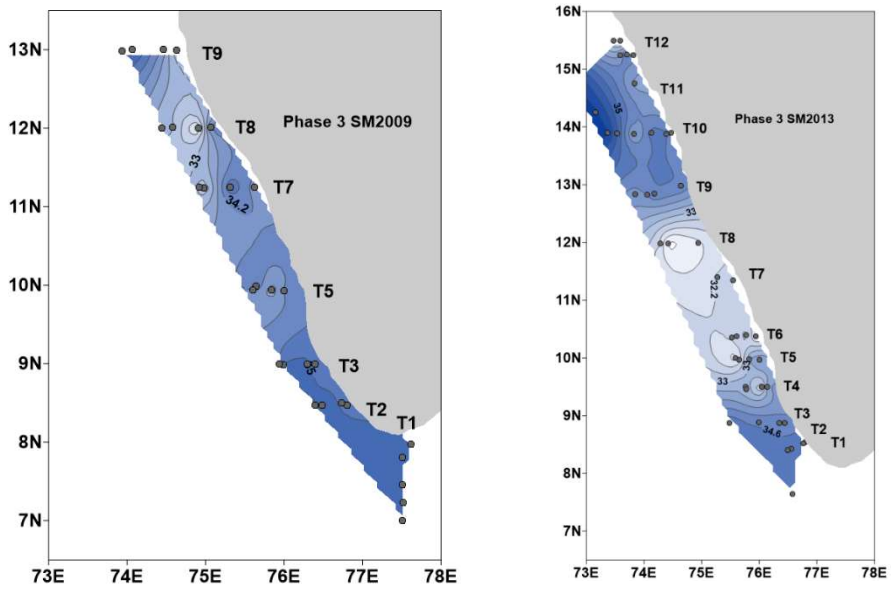
(b)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T5
T3
T2
T1
Phase 1 SM2010
35

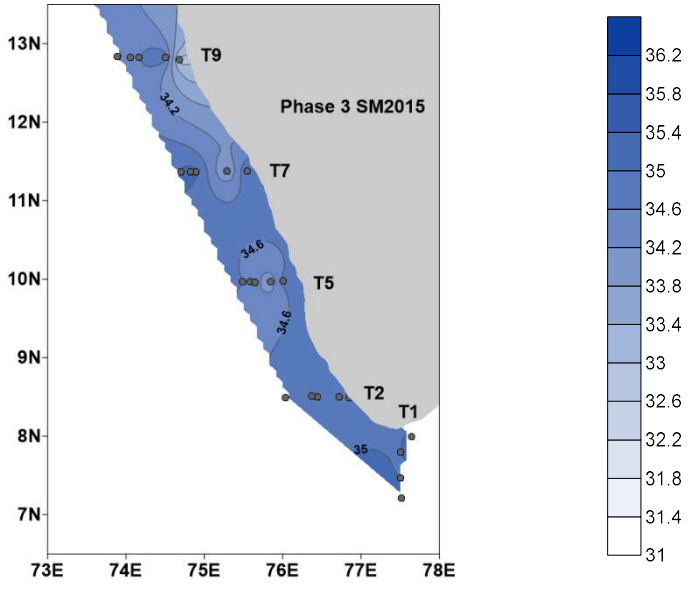
(c)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T5
T3
T2
T1
Phase 2 SM2010
35
34.6
35
35

(d)

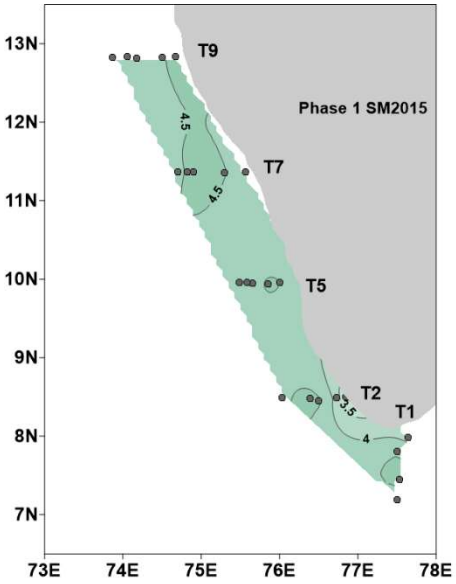


(e) **(f)**

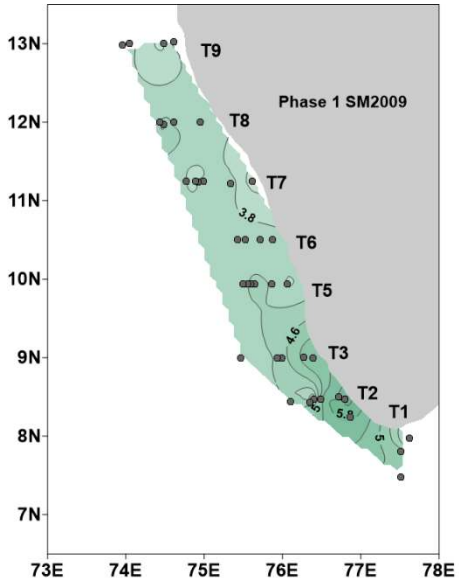


(g)

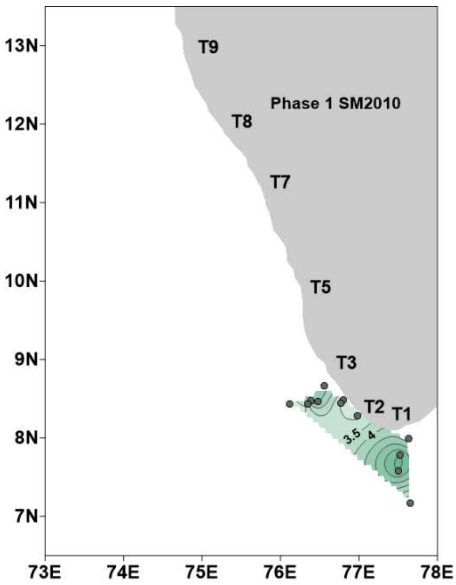
Fig.5.2. Variation in SSS during Phase-1 SM2015 (a), Phase-1 SM2009 (b), Phase-1 2010 (c), Phase-2 2010 (d), Phase-3 2009 (e), Phase-3 2013 (f), and Phase-3 2015 (g).


Phase 1 SM2015
T9
T7
T5
T2
T1
4.5
4.5
2.5
4
13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E

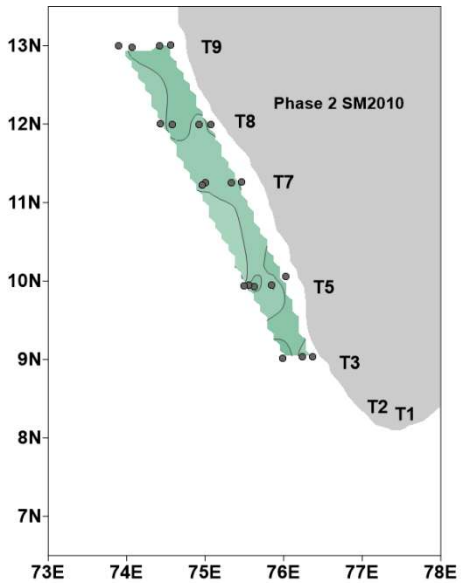
(a)


Phase 1 SM2009
T9
T8
T7
T6
T5
T3
T2
T1
3.8
4.6
5.5
5.8
5
13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E

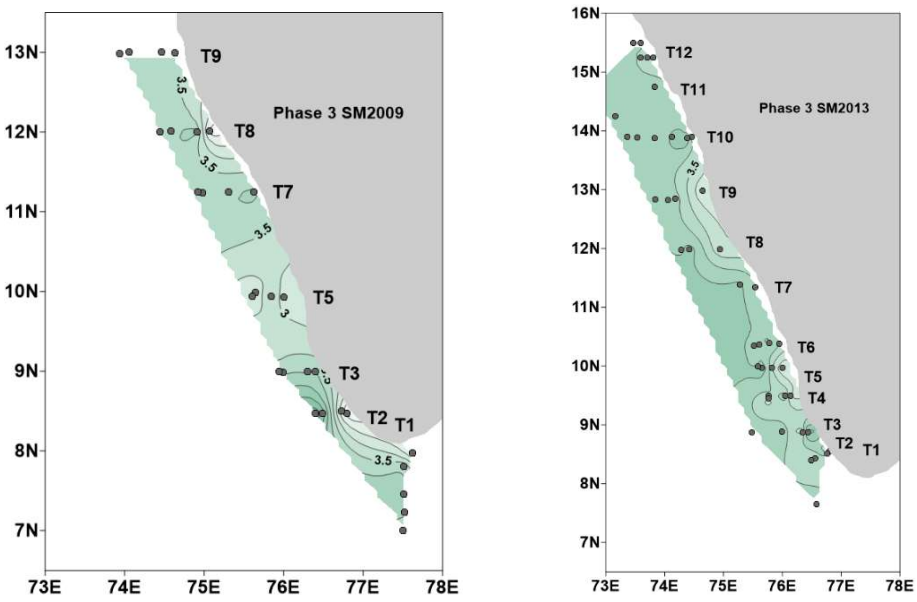
(b)


Phase 1 SM2010
T9
T8
T7
T5
T3
T2
T1
3.5
4
13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E

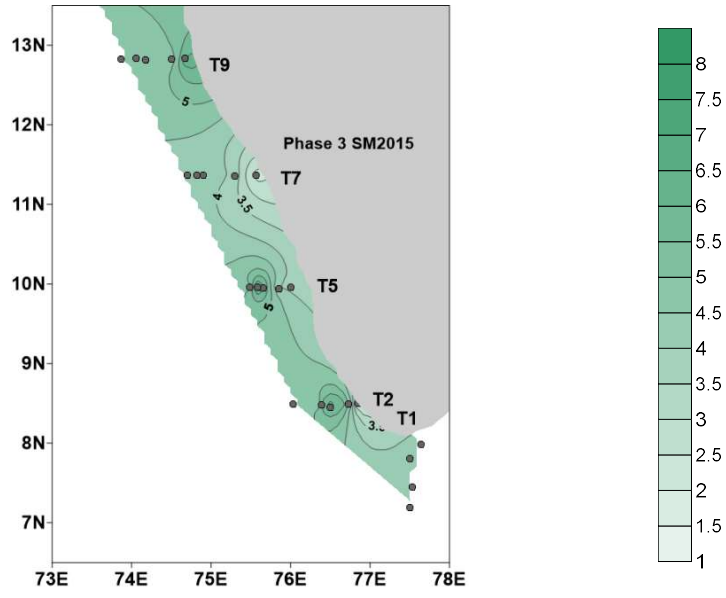
(c)


Phase 2 SM2010
T9
T8
T7
T5
T3
T2
T1
13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E

(d)

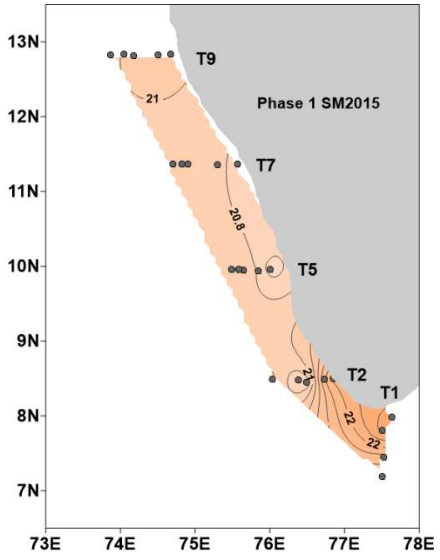


(e) (f)

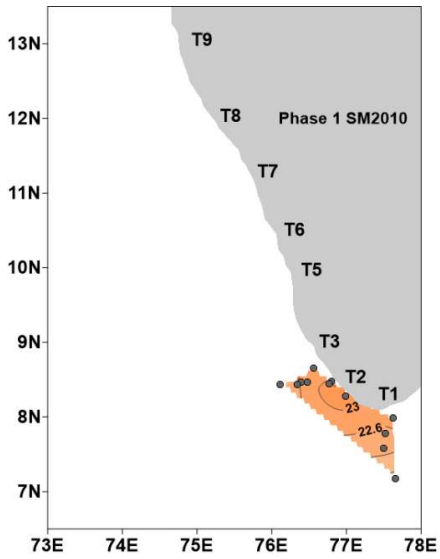


(g)

Fig.5.3. Variation in S-DO during Phase-1 SM2015 (a), Phase-1 SM2009 (b), Phase-1 2010 (c), Phase-2 2010 (d), Phase-3 2009 (e), Phase-3 2013 (f), and Phase-3 2015 (g)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 SM2015
21
20.8
21
22
22
Phase 1 SM2009
22.2
22.2
22.3
22.6
23

(a) (b)


13N
12N
11N
10N
9N
8N
7N
73E
74E
75E
76E
77E
78E
T9
T8
T7
T6
T5
T3
T2
T1
Phase 1 SM2010
23
22.6
Phase 2 SM2010
21
21.8
22.2
23
23.4

(c) (d)

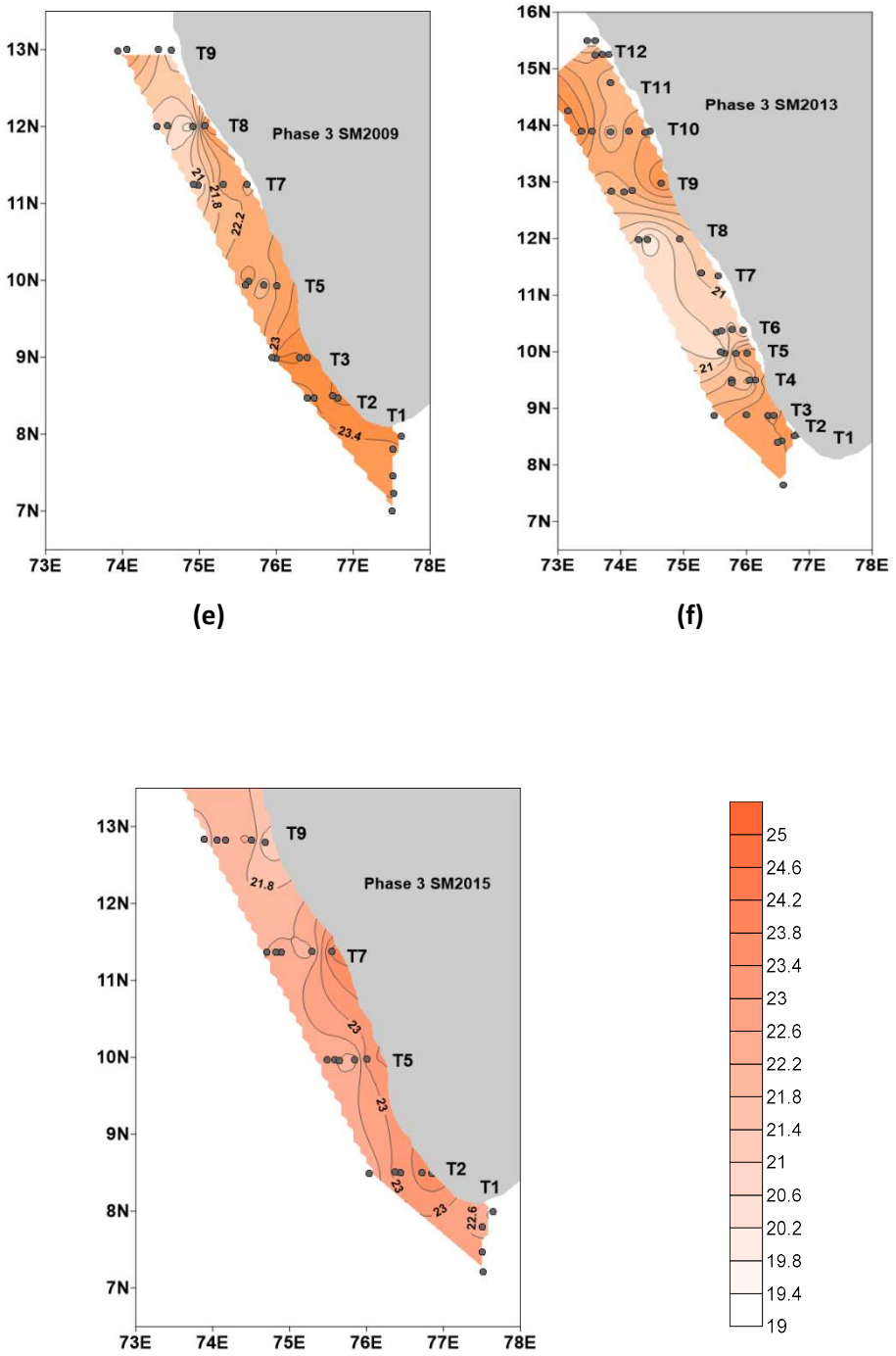


Fig.5.4. Variation in SSD during Phase-1 SM2015 (a), Phase-1 SM2009 (b), Phase-1 2010 (c), Phase-2 2010 (d), Phase-3 2009 (e), Phase-3 2013 (f), and Phase-3 2015 (g)

During the present investigations on the horizontal variations in abundance of oil sardine, anchovy and mackerel larvae along the SEAS during the different phases of monsoon, very high densities of larvae were encountered in certain pockets.

5.2.4. *Oil sardine eggs, larval abundance and retention areas*

Oil-sardine spawning grounds were identified and confirmed by the occurrence of eggs. The main spawning grounds of oil sardines were located in the near shore areas within a distance of 23.5 Km from the shore. In the present study, active spawning grounds of oil sardine were observed in the near shore waters off Valappad, off Kannur, off Calicut and off Kochi. The Ekman drift was moderate to low in most of the spawning sites. The SST ranged between 23.81°C to 28.76°C and SSS ranged between 33.99psu to 35.03psu. Details of *Sardinella longiceps* spawning grounds and environmental set up are given in Table 5.2.

Oil sardine larvae were recorded from 63 stations out of 234 stations covered along the SEAS during different phases of SM upwelling. Among the 63 stations, majority of the larvae (85%) were obtained from upwelling areas (51stations) which indicates that the oil-sardine larvae prefer coastal upwelling areas as their nursery grounds. The range of environmental conditions of these nursery grounds are; SST ranging from 23.80°C to 31.26°C, SSS from 31.60psu to 35.40psu and DO between 1.66 ml/L to 6.42 ml/L (Table 5.3). Oil sardine larvae were most abundant in sites having optimum range of environmental conditions ie; SST 26.21°C to 28.36°C (~94.66% larval abundance), SSS 34.50psu to 35.23psu (~95.42% larval abundance) and DO above 2.80ml/L (~99.96% larval

abundance). It was observed that all the early developmental stages from preflexion to post flexion were present in these larval aggregations.

During phase-1 SM 2009 very high densities of oil sardine larvae were recorded from Kollam 50m (39980 ind.10m^{-2}) and 100m (242 ind.10m^{-2}) stations. Our analysis indicates that these two stations were associated with the upwelling front. Strong horizontal gradients in SST, SSS and SSD (1.457^{o}C, 0.1868psu and 0.3413 Kgm^{-3} respectively) were observed in a distance of 31Km between the Kollam 50m and 100m stations. High chlorophyll - a concentration (4.66 mg m^{-3}) was recorded from the Kollam 100m station. The density of larvae were also high at Cape 100m station (213 ind.10m^{-2}) which recorded high chlorophyll a concentration (6.48 mg m^{-3}) with low Ekman drift (0.93cms^{-1}) resulting in limited offshore larval dispersal. At Trivandrum 100m, 200m & 500m stations larval abundance were higher and Ekman drifts were low (0.54cms^{-1}, 4.05cms^{-1} and 3.32cms^{-1}). The higher densities of sardine larvae from the 30m, 50m, 100m, 200m and 500m station (167 ind.10m^{-2}, 203 ind.10m^{-2}, 7148 ind.10m^{-2}, 447 ind.10m^{-2} and 102 ind.10m^{-2}) collections of Trivandrum transect during phase-1 SM 2010 is attributed to the influence of upwelling fronts. In addition to these frontal structures, the Kollam - Trivandrum sector was characterised by the presence of small mesoscale cold core eddy which enhances the overall productivity of the sector, besides providing conditions preferred by oil-sardines. Larval aggregations (454 ind.10m^{-2}) were also observed at the off Kannur 50m station. Though the location of sampling was relatively warm (SST 28.09°C), the region is identified as an outer periphery of a strong frontal structure with horizontal gradients 4.29^{o}C, 2.69psu and 3.53 Kgm^{-3} for

SST, SSS and SSD respectively. The low SSS (31.71psu) and SSD (19.89 Kgm^{-3}) in the 50m station where the larvae were observed indicate that river plumes might have contributed to the appearance of the fronts in this region. However, the low larval abundance (15 ind.$10m^{-2}$) in the near coastal area along this transect, may perhaps be due to the intense upwelling as evinced by the low SST (23.81°C) and a low DO (1.67ml/L at 5m) recorded. The oil sardine larvae were also found higher in the river plume areas off Aleppey 30m station (1420 ind.$10m^{-2}$) and the 50m station (154 ind.$10m^{-2}$), where the Ekman drift was weak (1.97cms^{-1} and 0.13cms^{-1}) respectively. Details of *Sardinella longiceps* larval retention areas and environmental set up are given in Table 5.3.

5.2.5. *Indian mackerel eggs, larval abundance and retention areas*

Spawning grounds of mackerel were observed at stations off Trivandrum (SZ) and off Kannur (NZ) within an SST range of 26.38°C to 29.08°C and SSS range 35.01psu to 35.46psu. Mackerel eggs were recorded on 2.6.2009 from the 50m station (975 eggs.$10m^{-2}$) and the 200m station (255 eggs.$10m^{-2}$) off the Trivandrum transect and on 11.6.09 from the 50m station (530 eggs.$10m^{-2}$) and the 100m station (1180 eggs.$10m^{-2}$) off the Kannur transect. Mackerel spawning grounds were located offshore, between 15.12km and 64.05km distance from the coast. Details of *Rastrelliger kanagurta* spawning grounds and associated environmental conditions are given in Table 5.4.

Indian mackerel larvae were recorded only from 36 stations out of 234 stations surveyed during the entire study period. Of the 4850 mackerel larvae collected, 67.98% were from the 50 m, 14.82% from the 100m, 13.96% from the 200m and 2.31% from the 500m isobaths (Table-5.5).

The 30m depth contour accounted for only 0.58% of the larvae collected. An offshore station located at 1450m depth off Cape yielded 7 mackerel larvae in the bongo collections made on 15.07.2013. Of this, 87.88% of the larvae were collected from 26 stations representing upwelling areas. South and North Zones accounted for 89.24% and 9.88% respectively in the larval abundance, whereas larval abundance in the Central Zone was only 0.88%.

It was also observed that unlike sardines, mackerel larvae completely avoided regions with ambient temperatures below 25°C. Even though mackerel larvae survive within the SST range (25.21°C to 30.65°C), SSS (31.61psu to 36.33psu) and DO (2.60 to 6.27 ml/L), they prefer an optimum range of SST 26.20°C to 27.75°C (~82.67% larval abundance), SSS 34.5psu to 35.5psu (~89.71% larval abundance) and DO above 3ml/L (~95.65% larval abundance). George (1989) noted that the most favorable temperature for mackerel larvae was between 27°C to 29°C and they dominantly occurred in the salinity range 33psu to 35psu.

In phase-1 SM 2009, peak abundance of mackerel larvae were observed at Kollam 50m (2935 ind.$10m^{-2}$), Trivandrum 200m and 500m stations (211 ind.$10m^{-2}$ and 112 ind.$10m^{-2}$ respectively). This SZ area was characterized by eddy, upwelling front and weak Ekman drift as discussed earlier which maintained the larval aggregation. In SM 2010, considerable number of larvae were obtained from off Trivandrum 100m (377 ind.$10m^{-2}$) and off Kollam 100m (264 ind.$10m^{-2}$) where the Ekman drifts were low (1.84cms^{-1} and 1.24cms^{-1}) respectively. Relatively high chlorophyll-a concentrations (4.31$mg.m^{-3}$ and 8.55$mg.m^{-3}$) were recorded from these stations. Mackerel larval aggregations where also observed at

Cape 50m upwelling front (200 ind.10m^{-2}) in phase-1 SM 2015 and from Kannur 200m (386 ind.10m^{-2}) where the Ekman drift was moderate (2.88cms^{-1}). Within the upwelling regions, mackerel larvae were observed mostly in river plume areas. They were recorded from the river plume areas of coastal stations off Kannur, Kochi, Alleppey, Mangalore and Goa with salinity range between 31.61psu to 32.60psu. A single record of larvae from Mangalore 30m depth station was observed at the river plume area outside the upwelling zone. Here the salinity recorded was 32.60psu and SST was 28.21°C. Details of *Rastrelliger kanagurta* larval retention areas and environmental set up are given in Table 5.5.

5.2.6. *Encrasicholina devisi eggs and larval abundance and retention areas*

Spawning grounds of *E. devisi* were observed at off Kannur, off Trivandrum and off Valappad. Eggs were recorded from areas with an SST range of 28.09°C to 30.6°C and SSS range of 34.57psu to 35.02psu. It was observed that the Ekman drift was very weak in these regions 0.85cms^{-1}, 0.28cms^{-1} and 5.2cms^{-1}. Details of *Encrasicholina devisi* spawning grounds and environmental set up are given in Table 5.6.

Encrasicholina devisi larvae had a wide range of distribution and were recorded from 83 out of the 234 stations surveyed. Only 20.37% of the larvae were associated with upwelling areas (28 stations). These larvae were predominantly found in areas with SST range (24.83°C to 31.32°C), SSS (31.61psu to 36.25psu) and DO (2.60 to 6.42 ml/L). Anchovy were abundantly found within an optimum range of SST 27.03°C to 31.13°C (~82.56% larval abundance). This shows that the anchovy larvae preferred slightly higher temperature range than the sardine and mackerel

larvae. The optimum range of SSS was 33.85psu to 36.2psu (~93.04% larval abundance) and DO above 2.95ml/L (~99.64% larval abundance). Aggregations of these larvae were present at upwelling fronts and eddies. Larvae were also abundant in the river plume areas off Trivandrum 203m (549 ind.10m^{-2}), off Kochi 50m (166 ind.10m^{-2}) and off Calicut 30m (727 ind.10m^{-2}). Details of *Encrasicholina devisi* larval retention areas and environmental set up are given in Table 5.7.

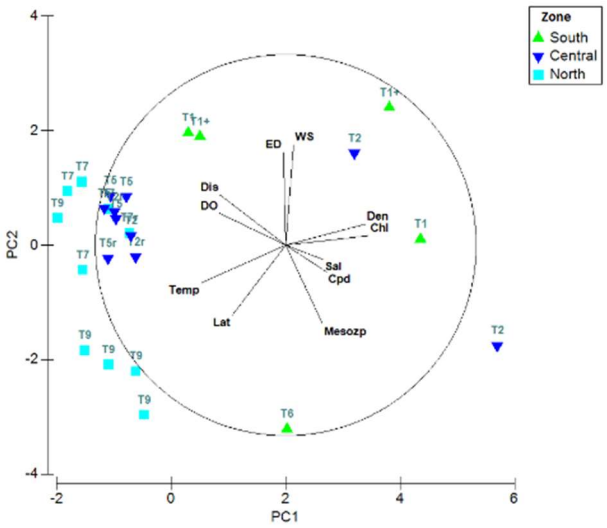
5.2.7. *Correlating larval abundance to environmental variables.*

Principal component analysis was carried out to analyse and visualise the spatial variations in environmental variables during different phases of SM and to correlate these with larval abundance of *S.longiceps*, *R.kanagurta* and *E.devisi* in the study area. In order to link the numerical abundance and distribution of sardine, anchovy and mackerel larvae with the prevailing environmental settings, the species abundance from each station during different phases of SM were superimposed as bubbles on the PCA biplot. The environmental variables included for PCA were Latitude (Lat), SST (Temp), Salinity (SSS), Dissolved Oxygen (DO), Density (Den), Chlorophyll (Chl), Wind Speed (WS), Ekman Drift (ED), Distance from the coast (Dis) Mesozooplankton abundance (Mesozp) and Copepod abundance (Cpd).

5.2.7.1. Phase-1 SM:

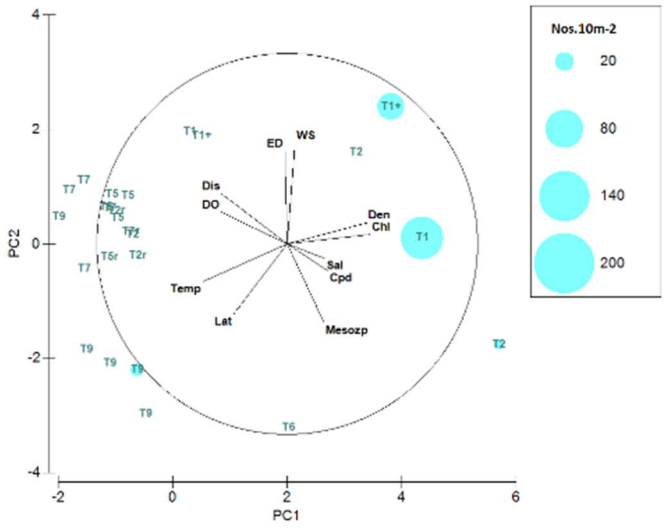
The results (Table 5.8) of the PCA of phase-1 2015 SM, indicates that PC1 (Eigenvalues 4.4) & PC2 (Eigenvalues 2.34) cumulatively explain 61.3% of the observed variations with Den (0.416) and Chl (0.434) having strong positive influence on PC1 and WS (0.526) and ED (0.489) on PC2 (Figure 5.6a). The Cape (T_1) coastal stations showing signatures

of upwelling such as relatively low SST (T_1,30m -27.83°C), dense waters, high chlorophyll, Ekman drift and high salinity were positioned towards the positive axis of the PC plot, implying the positive influence of upwelling on the SZ transects. The CZ transects are close to zero or oriented towards the negative axis, whereas the NZ transects lie away on this axis which indicates nil influence of upwelling on these transects. From Fig.5.6(b) to Fig.5.6(d), it can be interpreted that upwelling has a positive influence on the distribution and of oil sardine and mackerel larvae, whereas *E. devisi* larvae were absent in the SZ, indicating their avoidance of coastal upwelling areas. Higher abundance of anchovy larvae were observed in the shelf stations of central (CZ) and northern (NZ) transects characterized by higher SSTs.



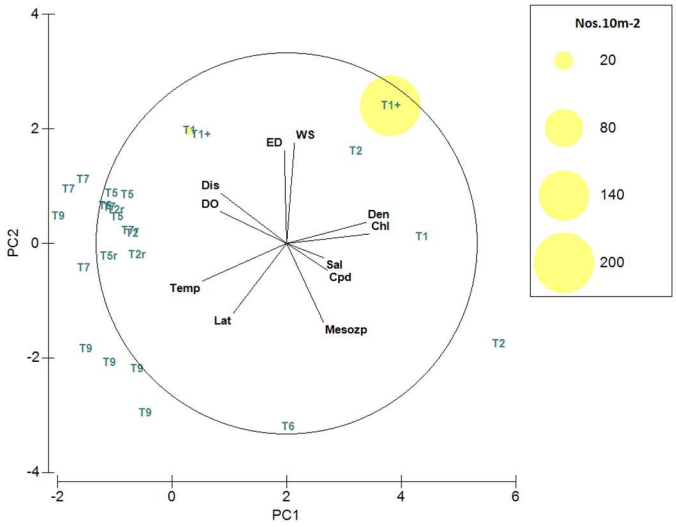
(a)

r river plume
***Eddy**
+ upwelling front

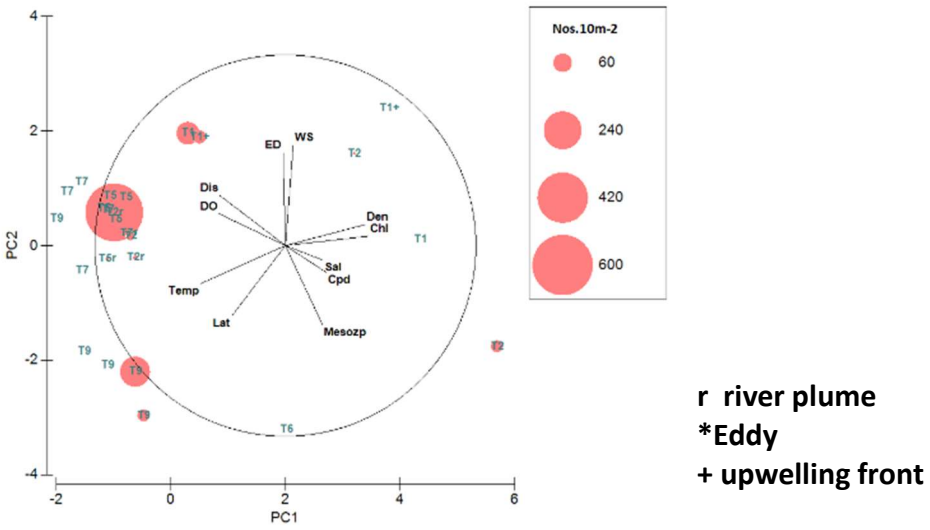


(b)

r river plume
***Eddy**
+ upwelling front



(c)

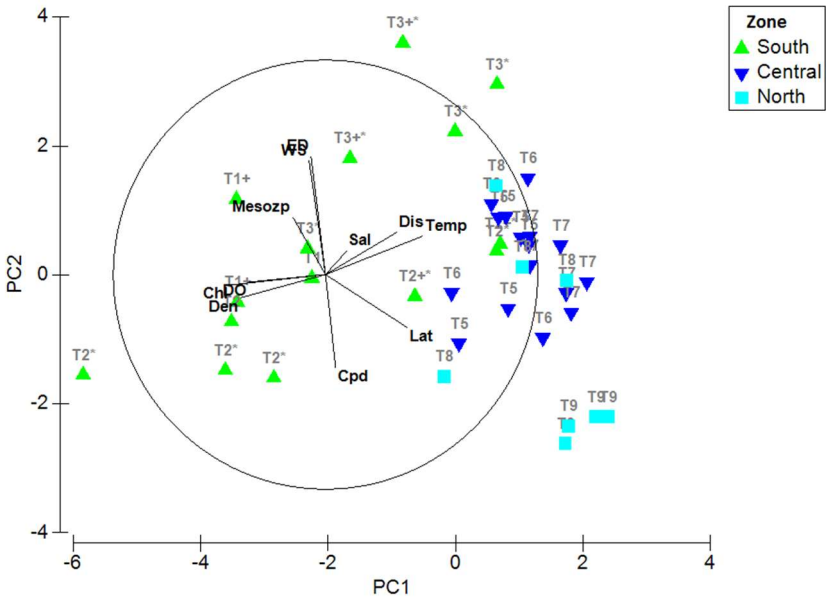


(d)

Figure 5.6 Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-1 2015 SM

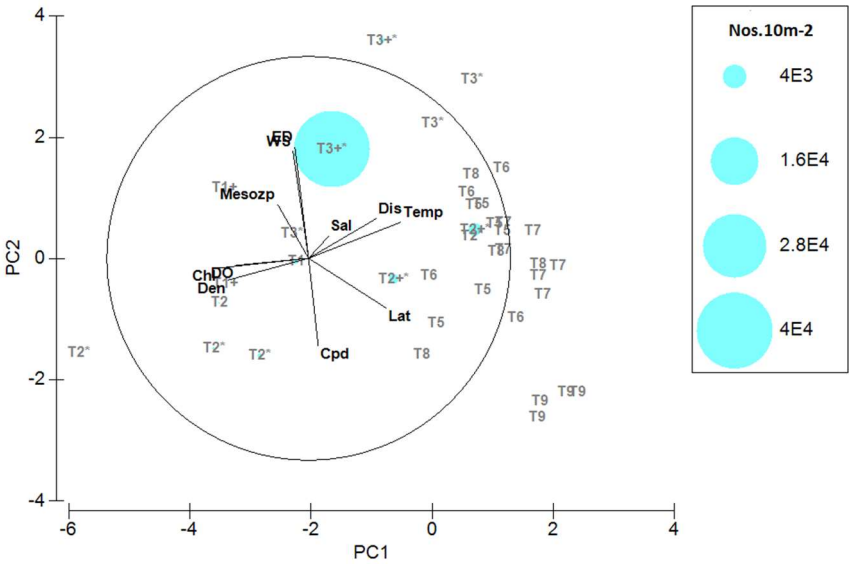
During phase-1 2009 (Table 5.9), PC1 (Eigenvalues 3.99) and PC2 (Eigenvalues 1.98) together explain only 54% of the variance of the PCA ordination. This may be due to the weak upwelling and the influence of the cold core eddy centered around Kollam-Trivandrum transects, as explained at para.5.2.1 above. Environmental variables such as Temp (0.455) and Dis (0.335) strongly influence PC 1 whereas WS (0.53) and ED (0.551) influence PC 2. Most of the SZ stations (Fig.5.7a) are oriented towards the centre of the PCA plot, indicating that these stations were under the influence of coastal upwelling and/or cold core eddy. Stations representing CZ and NZ were oriented more towards the periphery of the PCA plot which indicates that non-upwelling conditions prevailed in the offshore areas of SZ and along the complete stretches of the CZ & NZ.

Numerical abundance of oil sardine and mackerel larvae was higher in the coastal waters of SZ characterized by upwelled waters and in the eddy region (Figure 5.7b, 5.7c). Peak abundance of these larvae was observed in T_3, 50m station, which was distinguished by the occurrence of meso scale cold core eddy and upwelling front. Oil sardine larvae were completely absent in the CZ and NZ. Mackerel larvae show higher abundance in the SZ around the eddy area and poorly represented in the NZ. *E. devisi* larvae had a wide distribution and were present in all transects along the SEAS including the SZ offshore waters where the temperature was relatively higher (above 28.5°C). However, they are totally absent in the eddy region (Figure 5.7d).



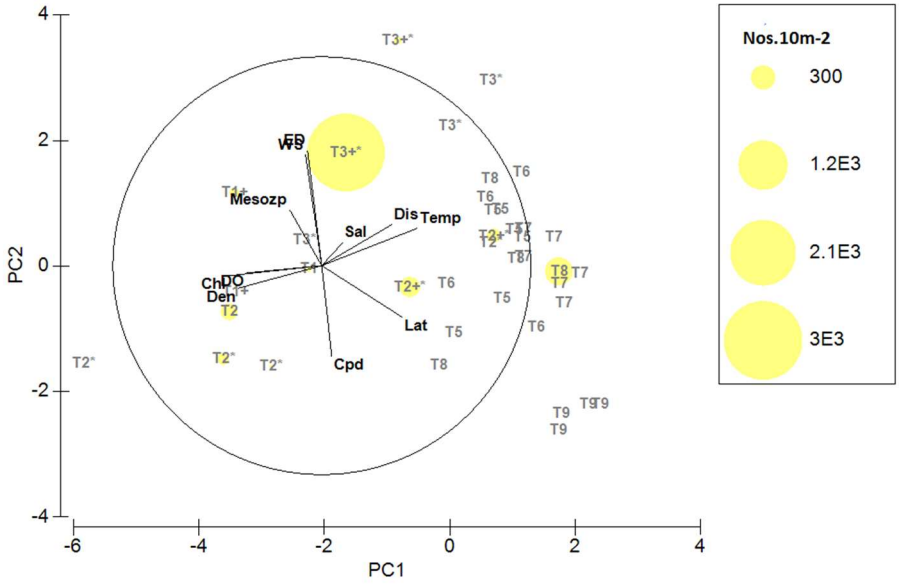
(a)

r river plume
***Eddy**
+ upwelling front

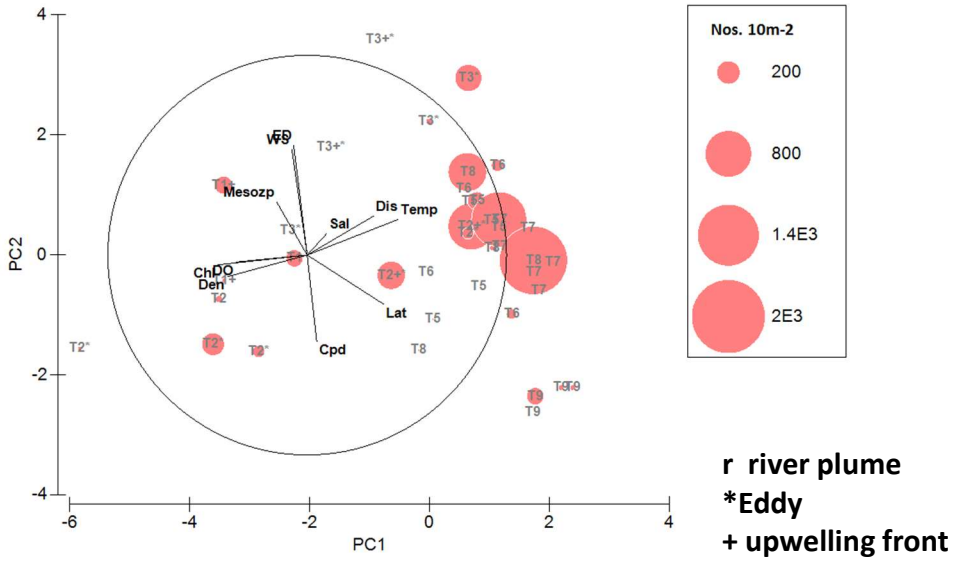


(b)

r river plume
***Eddy**
+ upwelling front



(c)



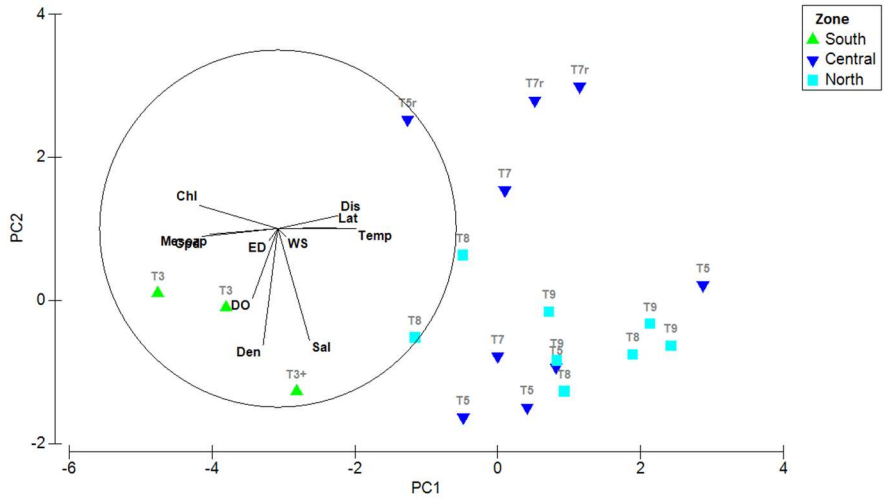
(d)

Figure 5.7. Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-1 2009 SM

5.2.7.2. Phase-2 SM :

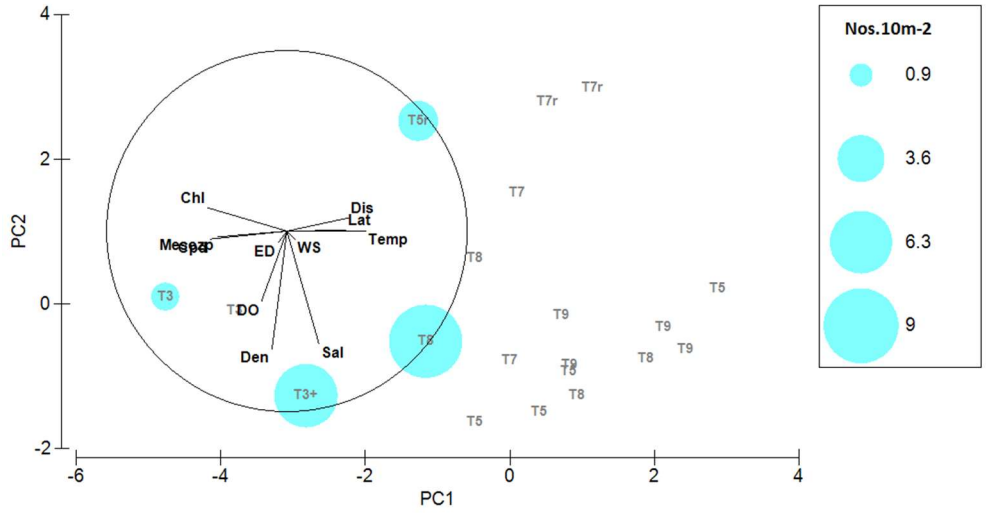
During phase-2 2010, PC1 (Eigenvalues 3.96) and PC2 (Eigenvalues 1.98) together explained 54% of the observed variations the results (Table 5.10). Environmental variables such as SST (0.437), Distance (0.341) and salinity (0.18) exerted a positive influence on PC1 (Figure 5.8a). The 100m station of T_3 transect (SZ) characterised by upwelling front was oriented towards the positive axis of PC1 and show high abundance of mackerel larvae and presence of sardine larvae. Mackerel larvae were predominately present in the T_3 shelf station showing preference to upwelled waters (5.8c).The coastal stations of T_3

lie on the negative axis of PC1 which implies weak upwelling and low abundance of sardine larvae (Fig 5.8b). Northern and the Central transects though oriented towards the positive axis of PC1, are located far away from the axis of the PCA plot, which implies that factors other than upwelling contribute towards this. In fact T_5 was in a river plume area (low salinity) and showed medium abundance of sardine and anchovy larvae, despite the absence of upwelling. *E. devisi* larvae were observed to be higher in the river plume areas of the central zone (Kochi, T_5, 50m, Calicut, T_7 30m) (5.8d) and other non-upwelling areas of the central and north zones.



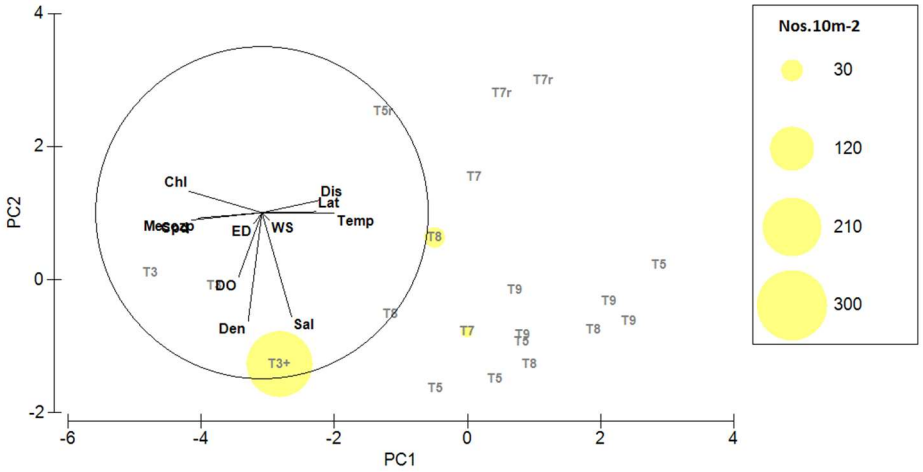
(a)

r river plume
***Eddy**
+ upwelling front

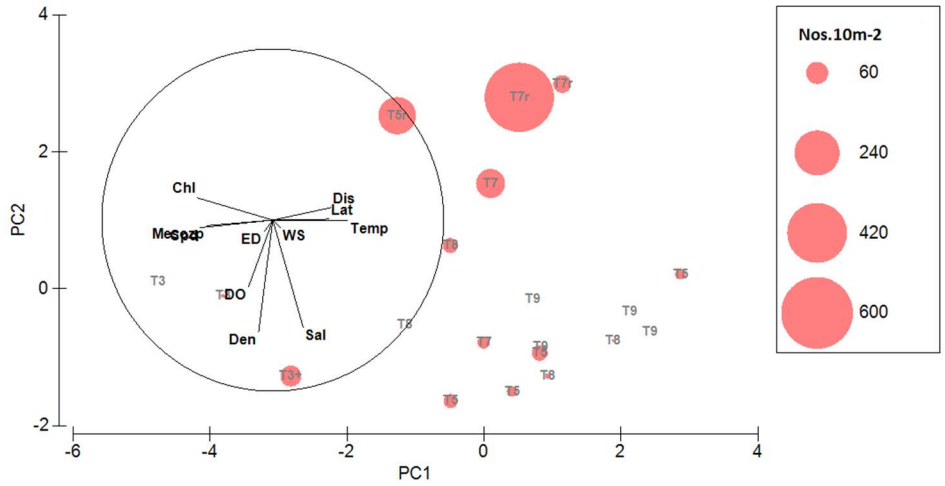


(b)

r river plume
***Eddy**
+ upwelling front



(c)



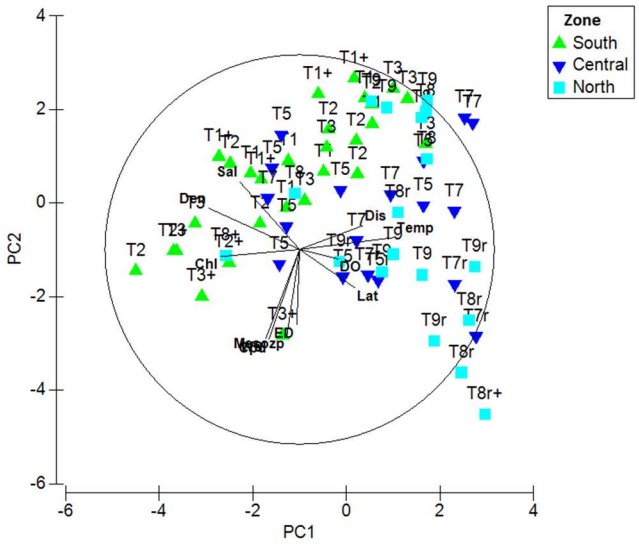
(d)

r river plume
***Eddy**
+ upwelling front

Figure 5.8. Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-2 2010 SM

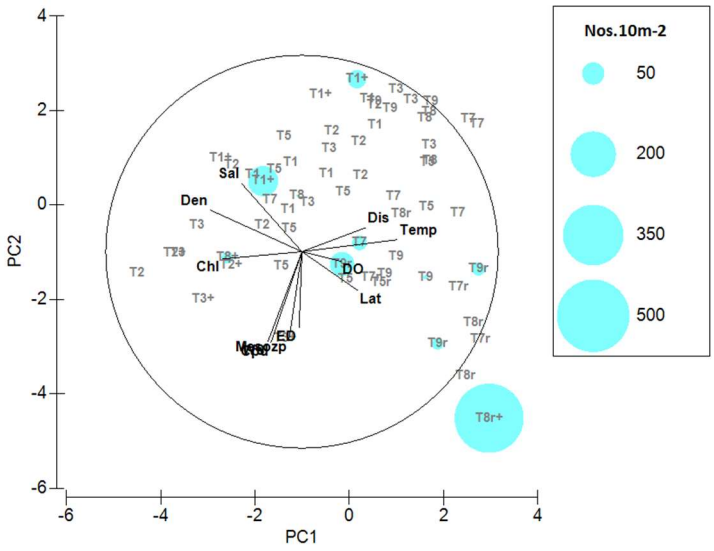
5.2.7.3. Phase-3: SM

In phase-3 2009, PC1 (Eigenvalues 3.49) and PC2 (Eigenvalues 2.81) together explained 57.3% of the site variations in PCA ordination (Table 5.11). Variables such as SST (0.485) and latitude (0.285) positively influenced PC1 and salinity (0.347) had a positive influence on PC2 (Figure 5.9a). Most stations of the south, central and the north zones were oriented towards the positive axis of PC1 & PC2 which show characteristics of upwelling (low SST, high density and high salinity). Peak abundance of sardine and mackerel larvae were present in the T_8 coastal station (NZ) characterized by riverine influence and upwelling front (5.9b &5.9c). A few sardine larvae were present in the T_1, 50m station. In this phase, *E. devisi* larvae was very few in number and only present in the shelf station of Kochi (T_5) (5.9d).



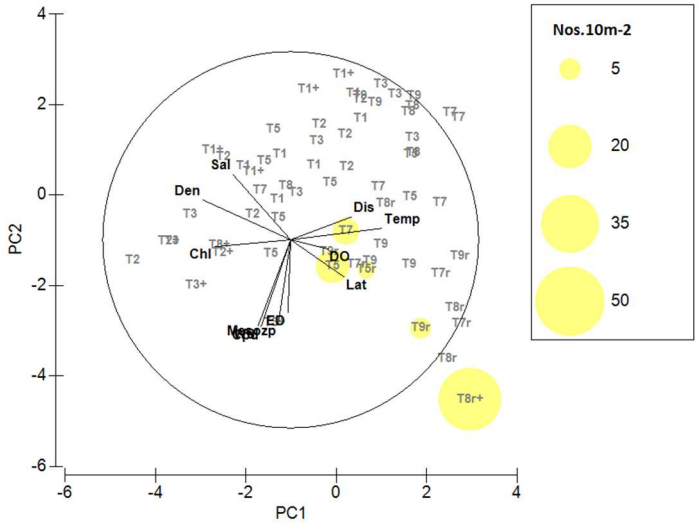
(a)

r river plume
*Eddy
+ upwelling front

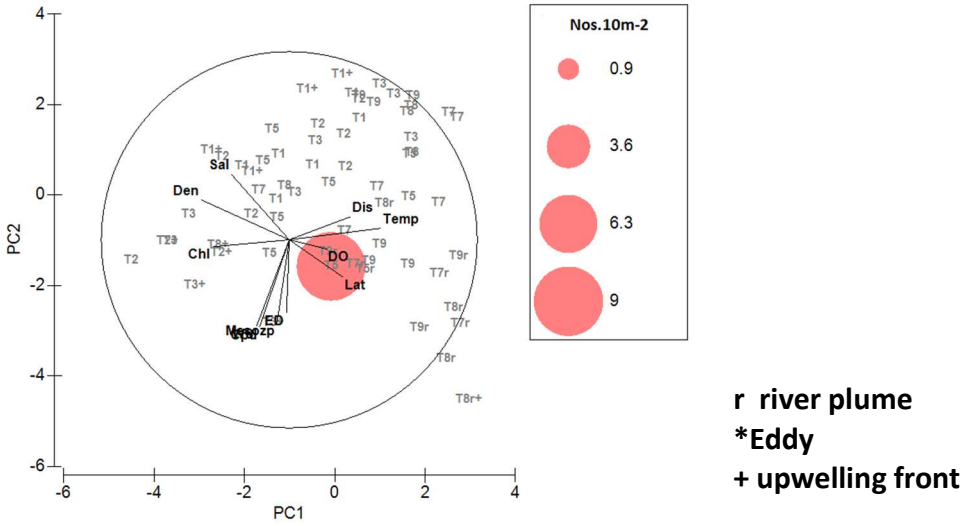


(b)

r river plume
***Eddy**
+ upwelling front



(c)

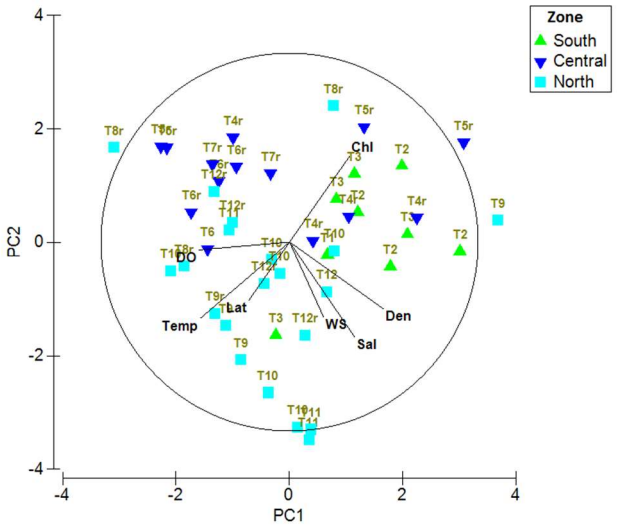


(d)

Figure 5.9. Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-3 2009 SM

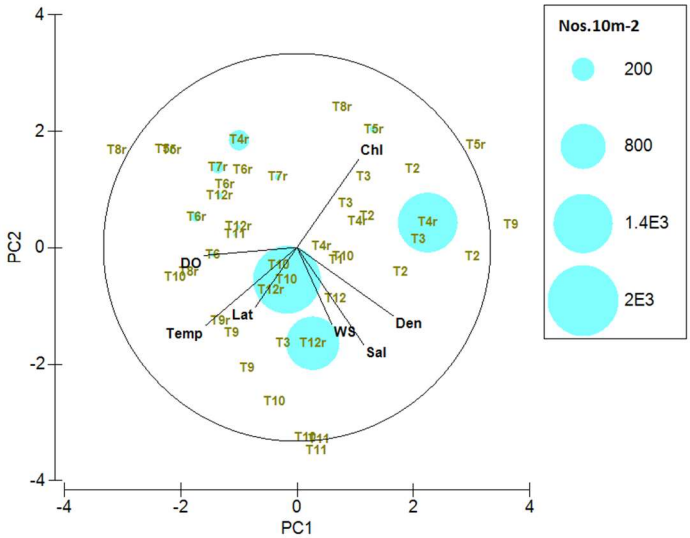
In phase-3 2013 (SM) PC1 (Eigenvalues 2.4) and PC2 (Eigenvalues 2.17) together explained 65.4% of the variance among the sites (Table 5.12 and Fig.5.10a). PC1 was positively influenced by salinity (0.345), density (0.498), chlorophyll (0.318) and wind speed (0.18) and PC2 by chlorophyll (0.454). The southern transects and the coastal stations of CZ were oriented towards the positive axis of PC1 and PC2 (upwelling area), whereas most of the NZ transects and stations were oriented towards the negative side (non-upwelling areas), but were under the influence of river discharges (T_8, T_9 & T_{12}). Temperature was relatively low in the NZ (26.29^{o}C ±1.15). In this phase, peak abundance of sardine larvae were observed higher in the coastal stations of northern transects (T_{10}, 50m and T_{12}, 30m - river plume) where upwelling was at its initial stages (5.10b). They were also higher in

the river plume areas of the central zone (T_4, Aleppey, 30m). Peak abundance of mackerel larvae were observed in the north zone predominately in the river plume areas (50m to 100m stations) of T_{12} (Goa) (5.10c). *E. devisi* larvae were abundant in the offshore waters of Kochi transect (T5) (5.10d).

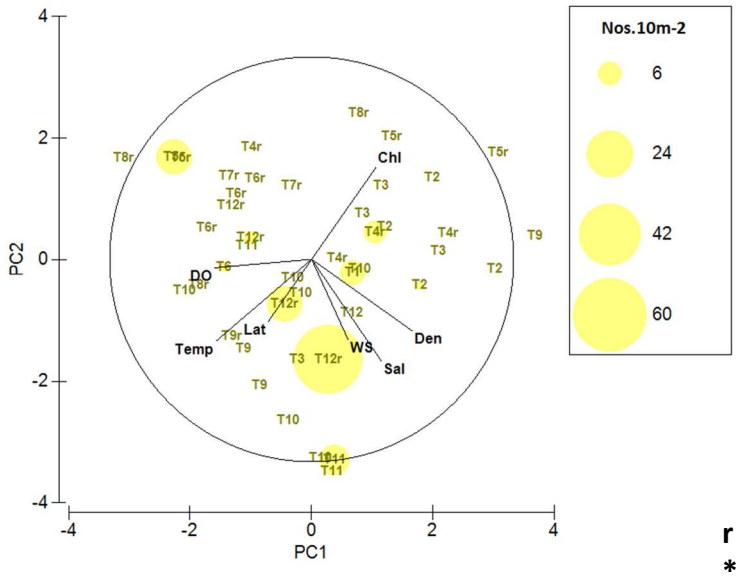


r river plume
***Eddy**
+ upwelling front

(a)

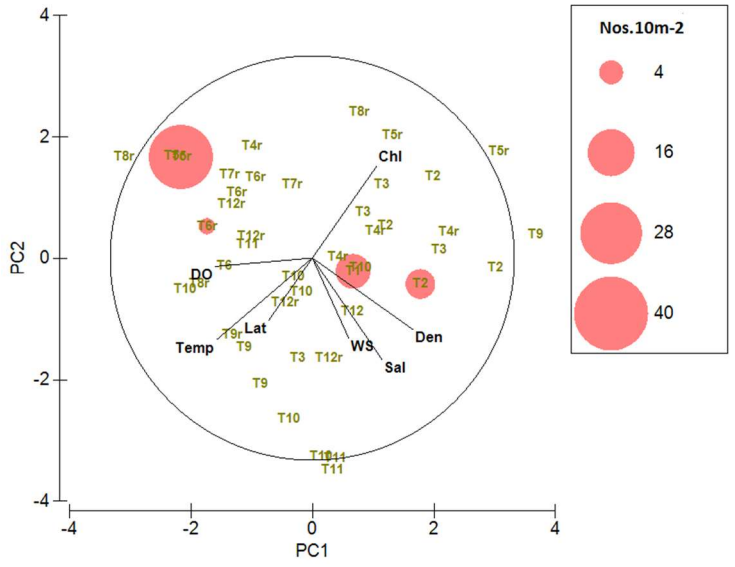


(b)



(c)

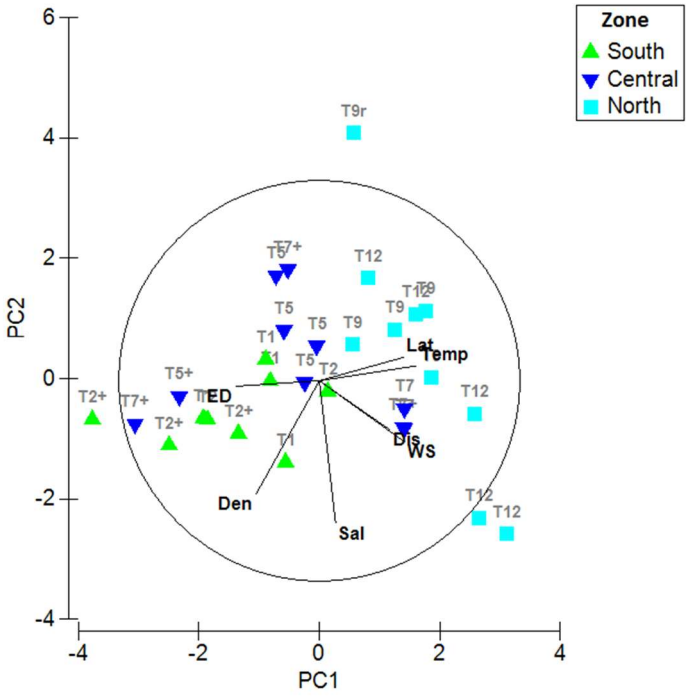
r river plume
*Eddy
+ upwelling front



(d)

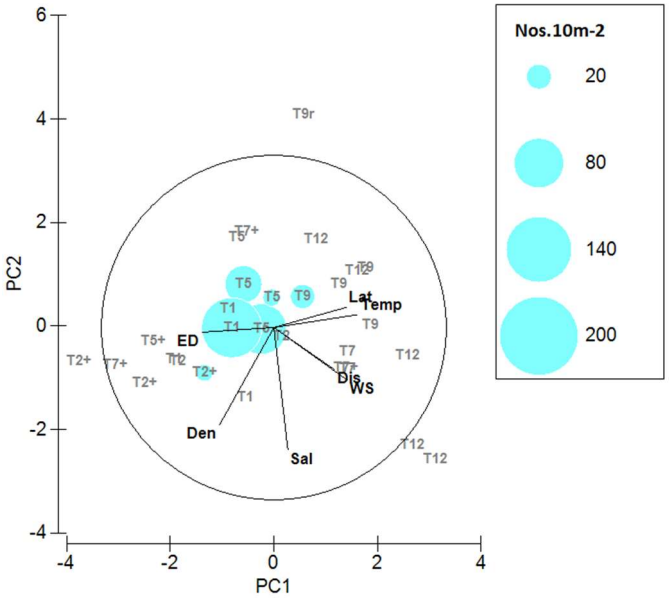
Figure 5.10. Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-3 2013 SM

Results (Table 5.13) of the PCA analysis of phase-3 2015 shows that 70.7% of the variance among the sites were explained by PC1 (Eigenvalues 3.16) and PC2 (Eigenvalues 1.79). Variables such as latitude (0.421), SST (0.486), wind speed (0.428) and distance (0.353) had strong positive influence on PC1. The positive axes of PC1 & PC2 were occupied by the Central and Northern transects and stations (Figure 5.11a). Signatures of upwelling were evident in T_2 (Trivandrum transect), T_5 (Kochi transect) and T_9 (Calicut transect). Sardine larvae were found higher in the central zone (Kochi, T_5 transect) and was present in T_1 (50m), T_2 (100m) and T_9 (50m) station (5.11b). Mackerel larvae were almost absent in this phase (5.11c). *E.devisi* larvae were abundant in the offshore stations of T_{12}, 200m (Goa) (5.11d). They were present in all the transects even though they were poorly present.



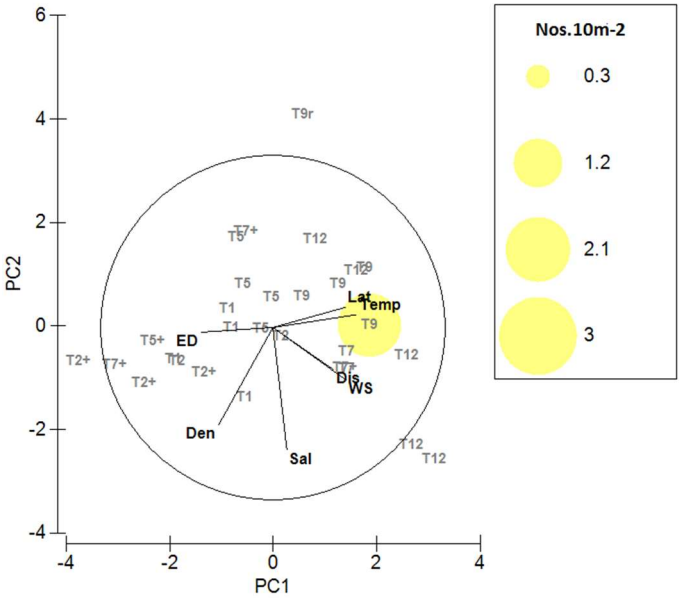
r river plume
***Eddy**
+ upwelling front

(a)

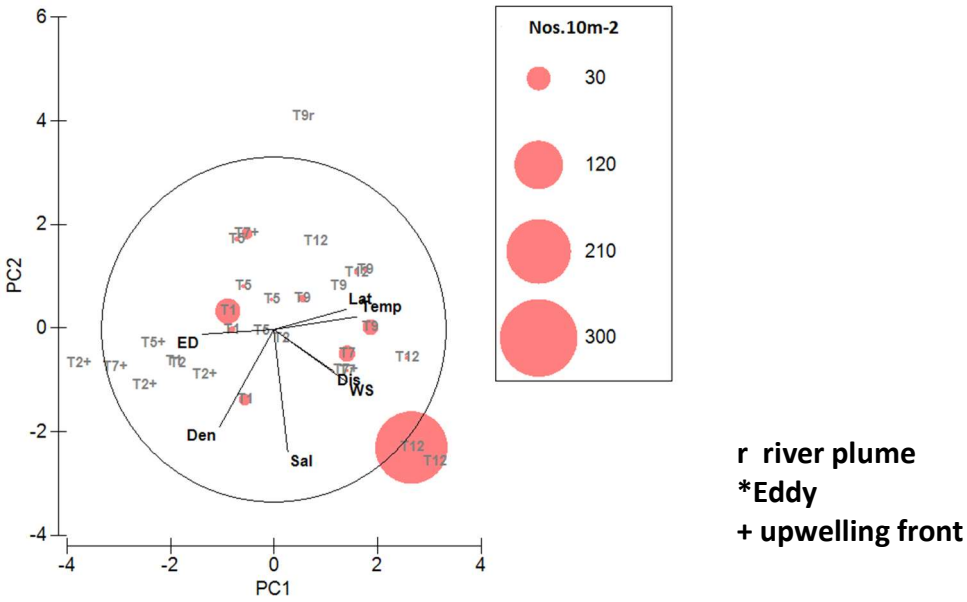


(b)

r river plume
*Eddy
+ upwelling front



(c)



(d)

Figure 5.11. Principal component analysis of (a) environmental variables, with superimposed bubbles that indicate numerical abundance of (b) *Sardinella longiceps,* (c) *Rastrelliger kanagurta and* (*d*) *Encrasicholina devisi* of Phase-3 2015 SM.

In phase-1 of 2009, 2010 and 2015 signatures of upwelling starts at the southern end. It was characterised by relatively low temperature, dense waters, high chlorophyll and high salinity in the southern transects. The CZ and NZ was devoid of upwelled waters. It was observed that in phase-1, oil sardine and mackerel larvae clearly showed higher abundance in the upwelled waters of the SZ. They were higher in the stations were upwelling was at its initial stages. It was observed that peak abundance (larval aggregations) of oil sardine and mackerel larvae were observed in areas of meso scale cold core eddy and upwelling front. Even though anchovy larvae were present in the upwelled waters, they were abundant in the shelf stations of central and northern transects showing their preference to non-upwelled waters characterised by higher temperature.

They showed a wide range of distribution. In phase-2 2010, the signatures of upwelling were present in the T_3 transect. The NZ and CZ was devoid of upwelled waters. Sardine and mackerel larvae preferred SZ especially in frontal regions. In this phase, anchovy larvae were abundantly present in the central zone (T_5 and T_7). They had wide range of distribution preferring shelf, non-upwelled waters. In phase-3 2009, 2013 and 2015, the upwelling was established in the SZ and CZ and was initialising in the NZ. Peak abundance of sardine larvae were present in NZ where the upwelling was at its initial stages. In this survey the sardine larvae were found higher in the central zone. They were higher at areas where riverine influence and upwelling front was present. In this phase, *E. devisi* larvae were very few in number and only present in the shelf station of Kochi (T_5). *E. devisi* larvae showed preference to the northern shelf stations even though they were poorly present in all the zones. Mackerel larvae were almost absent in this phase.

5.3. Discussion

In the present study, the larvae of oil sardine and mackerel were present predominately in upwelling areas. Oil sardine and mackerel larvae exhibited a northward progression of larval distribution as the season advances. The variations in the environmental parameters in the region brought about by the upwelling phenomenon cause remarkable influence on the distribution and abundance of the larvae of pelagic fishes. Recruitment of pelagic fish stocks like sardine and rastrelliger are significantly influenced by their ambient environmental variability. Longhurst and Wooster (1990) noted that oil sardine abundance was higher when the onset of monsoon was earlier. Bakun *et al.,* 1998 noted that clupeoid fishes preffered to spawn in areas where the seasonal

average of W^3 index does not exceed 250 m^3 s^{-3}. Most of the spawning sites in the present study were W^3 index was less than 250 m^3 s^{-3}. Santos *et al.,* 2018 reported that the recruitment peaks of *Sardina pilchardus*, varies latitudinally depending on the seasonal variability of offshore transport. Shin *et al* (1998) gave generalization on the clupeoids reproductive strategies in the world's major upwelling ecosystems as in low latitude upwelling ecosystems, the reproduction timing of sardines coincides with wind speed between 5 to 6ms^{-1}.

In the present observations, anchovy larvae inhabited mainly non-upwelling areas. Anchovy larvae had a wide range of distribution. They were predominately present in shelf waters. Bakun 1982, observed a consistent pattern of avoidance of maximum upwelling centres by anchovies. They prefer to occupy regions of low turbulent mixing in the downstream of upwelling maxima which is characterised by intense turbulent mixing and offshore transport. Brochier *et al.*, 2008a, Shen *et al.,* 2017 pointed out that the anchoveta prefers spawning in areas which favour retention in the Humbolt Current system.

As the small pelagic fishes are planktivores, they gather in coastal upwelled waters where the plankton production is high (Devaraj *et al.,* 1997). Parrish *et al.,* 1981 pointed out that in the California Current System, pelagic fishes were dominant in the southern part where upwelling was present throughout the year and the spawning grounds of these fishes were present primarily in weak upwelling areas. In the northern part, where the upwelling was seasonal, had demersal fishes in addition to pelagic. The influence of upwelling on the survival of fish larvae can vary geographically (Parrish *et al.,* 1981). Ryther (1969) noted that, pelagic fishes with relatively short food chains dominate in

upwelling areas while demersal fishes with long food chain dominate in higher latitudes. In upwelling areas, offshore transport and turbulence adversely affects the survival of ichthyoplankton (Smitha, 2010). Strong wind intensity can lead to enhanced enrichment but it can cause higher water turbulence which leads to low concentration of particles (Cury and Roy, 1989; Lluch- Cota *et al.,* 1999).

Mass aggregations of pelagic fishes larvae were observed at upwelling thermal fronts, eddies and river plumes. There is increasing evidence that fish larvae maintain their position in thermal fronts situated in near shore areas (Bakun, 1996, 1998). These upwelling induced retention areas act as nursery grounds for the developing larvae were the food availability for the first feeding larvae is high which increases the chances of survival and recruitment. The frontal structure at this region act as a retention area, and enhances total plankton supported by upwelling. These sites of aggregation within the spawning area also reduces the dispersion of larvae offshore (Quiros *et al.,* 2003). It is not upwelling alone but upwelling and retention of the larvae in the frontal areas together provide most suitable reproductive habitat for the survival of the larvae (Roy, 1998). These larval aggregations were confined to the upwelling frontal structures formed where the upwelling was at its initial stages. This suggests that there is some degree of retention of developing larvae in this area. According to Bakun 2006, developing larvae which are weak swimmers are passively carried to the convergent zone of the frontal structures where the food particles are concentrated. Mesoscale eddies propagating in the shelf break influence the larval assemblages of shelf and slope (Atwood *et al.,* 2010). Study of Lobel and Robinson, 1986

indicates that mesoscale eddies can entrain and entrap reef fishes for sufficient residence time to complete their pelagic developmental phase. Eddies can enhance the zooplankton abundance which contribute to the larval diet (Govoni *et al.,* 2009). Studies on larvae of Spanish mackerel discloses that the availability of fish prey is an important determinant of growth rate of these larvae (Shoji and Tanaka 2003) as they are almost piscivoros (Jenkins *et al.,* 1984, Finucane *et al.,* 1990, Shoji *et al.,* 1997) from the first feeding stage. The larval growth rates of King Mackerel was higher in larval assemblages (De Vries *et al.,* 1990) favoured by the retention areas. Mesoscale eddies and frontal structures supports the ocean triad hypothesis put forward by Bakun (1998, 2006) explaining concentration, enrichment and retention of larvae and this coexist with diatom dominant phytoplankton. They enhances the biological productivity and thereby increases larval survival and recruitment success. It was evident from the study that the larvae seems to prefer front of river plumes or the areas with riverine influences. Studies documenting enhanced densities of larval fish at plume fronts have emphasised the passive accumulation of positively buoyant or surface organisms (Govoni *et al*. 1989; Govoni and Grims 1992; Thorrold *et al.*, 1994).

Eddies, upwelling frontal regions and river plumes located not far from the spawning grounds of pelagic fishes can be the nursery sites of these pelagic fishes where their larvae are nourished. These mesoscale hydrodynamic structures of the SEAS influence the horizontal distribution of ichthyoplankton and makes the area potentially favourable to recruitment.

Table 5.1 Monthly average of Environmental conditions and Productivity. (Number of Observations in each month is given in brackets along with the average and range values for each variable).

Zone	Phase	SST (°C)	SSS (psu)	S-DO (ml/L)	MLD (m)	Chl-a (mg.m-3)	MesoZP (ml.m3)
South Zone	Phase-1 (36)	24.835 - 30.693 27.712 ± 1.579	33.839 - 35.563 34.862 ± 0.244	2.619 - 6.424 4.363 ± 0.987	6 - 38 13.77 ± 7.583	0.08 - 22.745 3.804 ± 5.330	0.088 - 13.33 3.22 ± 2.602
	Phase-2 (3)	26.23 - 26.97 26.523 ± 0.393	34.3 - 34.93 34.587 ± 0.313	4.677 - 6.273 5.228 ± 0.905	8 - 15 11 ± 3.606	6.703 - 8.977 8.077 ± 1.209	0.889 - 5.2 2.757 ± 2.212
	Phase-3 (46)	23.054-28.867 26.009 ± 1.623	34.258-35.298 34.911 ± 0.229	1.675-5.821 3.724 ± 0.914	6-34 15.47 ± 7.714	0.299 - 24.936 5.073 ± 5.477	0.24-13.33 2.160 ± 2.688
Central Zone	Phase-1 (27)	28.474 - 31.369 29.825 ± 1.009	83.752 - 35.559 34.789 ± 0.487	3.179 - 4.676 1.117 ± 0.366	6 - 31 14.625 ± 8.107	0.185 - 4.675 2.263 ± 1.981	0.022 - 3.273 0.932 ± 0.941
	Phase-2 (9)	28.18 - 28.852 28.532 ± 0.249	33.602 - 35.47 34.731 ± 0.821	3.216 - 5.763 4.689 ± 0.758	8 - 34 15.889 ± 7.944	0.25 - 2.732 1.841 ± 1.040	0.004 - 2.8 0.664 ± 0.921
	Phase-3 (42)	22.684 - 28.969 26.553 ± 1.435	31.604 - 35.136 33.747 ± 1.033	1.193 - 5.156 3.474 ± 0.881	6 - 28 9.238 ± 4.726	0.355 - 11.857 2.628 ± 2.950	0.16 - 5.333 2.095 ± 1.320
North Zone	Phase-1 (13)	28.576 - 31.355	34.471 - 35.722	3.209 - 4.875	6 - 33	0.093 - 4.695	0.018 - 1.5

	29.832 ± 1.202	34.999 ± 0.408	4.145 ± 0.409	14.111 ± 8.724	2.334 ± 1.952	0.780 ± 0.469
Phase-2	28.074 - 28.8	34.471 - 35.355	4.52 - 5.559	6 - 24	0.103 - 2.732	0.004 - 1.333
(8)	28.428 ± 0.304	35.009 ± 0.378	5.008 ± 0.312	15.5 ± 6.969	1.146 ± 1.154	0.466 ± 0.401
Phase-3	23.59 - 28.800	31.226 - 36.357	1.667 - 5.797	6 - 50	0.040 - 7.852	0.4 - 5.917
(50)	27.154 ± 1.269	34.174 ± 1.269	3.907 ± 0.656	13 ± 11.307	1.718 ± 1.833	1.755 ± 1.666

Table 5.2. Details of *Sardinella longiceps* spawning grounds and environmental set up

Transect	Date	Depth (m)	Distance from coast (Km)	Egg abundance (Nos.10m^{-2})	SST (°C)	SSS (psu)	S-DO (ml/L)	Density (Kgm^{-3}	Ekman drift (cm s^{-1})	Wind Speed ms^{-1}	W3 index (m^3.s^{-3})	Chl-a (mg.m^{-3})	MesoZP (ml.m^{-3})	Cpd	Remarks
Valappad	12.06.09	30	18.7	666	28.76	35.03	3.95	22.17	1.19	7.69	454.76	4.65	0.1	640	
Calicut	07.08.09	30	16.58	108	26.59	33.99	4.096	22.09	0.96	4.42	86.35	0.56	4.4	175.2	RP
Kannur	06.08.09	30	13.25	215	23.81	34.40	1.67	23.42	22.96	5.81	196.12	5.85	0.4	104	UF
Kochi	15.08.15	32	23.5	5871	24.44	34.77		23.34	0.67	3.6	46.67	5.87			UF
Kannur	12.08.15	31	20	51640	24.54	34.37		23.01	36.34	7.9	493.03	3.64			

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.3 *Sardinella longiceps* larval retention areas: Environmental set up

Transect	Date	Depth (m)	Larval abundance (Nos.10 m^{-2})	SST (^oC)	SSS (psu)	S-DO (ml/L)	Density (Kgm^{-3})	Ekman drift ($cm\ s^{-1}$)	Wind Speed ms^{-1}	W^3 index ($m^3.s^{-3}$)	Chl-a ($mg.m^{-}3$)	MesoZP ($ml.m^{-3}$)	Cpd	Remarks
Cape	30.05.09	100	213	27.03	34.89	4.68	22.63	0.93	6.03	219.26	6.48	3.82	2610.91	ED Low
Cape	05.06.10	50	15657	27.88	34.88	6.08	22.34	81.72	10.11	1033.36	0.93	8.00	512.00	Up F
Cape	07.06.10	75	125	27.87	34.87	6.08	22.32	45.96	9	729	4.31	8.00	512.00	Up F
Cape	30.05.15	33	101	27.83	34.96	3.83	22.42	12.14	4.6	97.34	3.83	1.00	52.00	Up F
Cape	18.08.15	50	117	28.36	35		22.27	0.84	5.4	157.46				UpF, ED Low
Trivandrum	2.06.09	100	183	26.38	35.01	5.74	22.92	0.54	1.16	2	4.56	4.67	426.67	Eddy, ED Low
Trivandrum	2.06.09	200	783	26.87	35.41	2.95	23.06	4.05	2.23	11	1.05	1.71	426.67	Eddy, ED Low
Trivandrum	1.06.09	500	1329	29.19	34.89	4.54	21.92	3.32	4.79	110	0.36	0.68	1140.00	Eddy, Up F, ED Low
Trivandrum	7.06.10	30	167	25.22	34.27	3.04	22.73	34.17	6.52	277	1.38	2.22	8444.44	Up F
Trivandrum	7.06.10	50	203	24.97	34.78	2.89	23.18	15.92	7.13	362	0.93	3.43	1039.24	Up F
Trivandrum	9.06.10	100	7148	26.45	34.92	4.63	22.83	1.84	4.39	85	4.31	0.67	344.83	Up F, ED Low
Trivandrum	9.06.10	200	447	27.27	35.21	4.96	22.78	0.01	3.51	43	1.23	0.90	1348.65	Up F, ED Low
Trivandrum	09.06.10	500	102	28.32	35.24	3.13	22.47	82.14	10.49	1154.32		0.46	1125.54	Up F
Kollam	3.06.09	50	39980	27.76	34.94	5.13	22.42	1.89	6.64	293	1.1	13.33	37.33	Eddy, Up F, ED Low
Kollam	4.06.09	100	242	29.22	35.13	4.46	22.09	30.38	6.66	295	4.66	13.33	37.33	Eddy, Up F, ED Low

Alleppey	19.07.13	30	1420	24.75	33.77	2.81	22.49	1.97	3.22	33.39	1.77	3.48	1825.39	ED Low, River Plume
Alleppey	19.07.13	50	154	25.41	32.10	4.39	21.03	0.13	0.762	0.44	1.01	1.10	337.60	ED Low, River Plume
Kannur	06.08.09	50	454	28.09	31.71	4.15	19.89	21.43	6.04	220	0.39	4.00	3048.00	River Plume
Bhatkal	15.08.13	52	1833	26.98	34.81	4.53	22.58		1.47		2.88			ED Low
Goa	18.08.13	32	1134	26.24	34.71	3.74	22.74				0.44			ED Low, River Plume

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.4. Details of *Rastrelliger kanagurta* spawning grounds and environmental set up

Transect	Date	Depth (m)	Distance from coast (Km)	Egg abundance (Nos.10m^{-2})	SST (^{o}C)	SSS (psu)	S-DO (ml/L)	Density (Kgm^{-3})	Ekman drift (cm s^{-1})	Wind Speed ms^{-1}	W3 index (m^{3}.s^{-3})	Chl (mg.m^{-3})	MesoZP (ml.m^{-3})	Cpd	Remarks
Trivandrum	2.06.09	50	15.12	975	26.38	35.01	5.74	22.99	2.44	1.99	7.88	8.89	5.33	2524	Eddy
Trivandrum	2.06.09	200	44.64	255	26.87	35.40	2.95	23.06	4.05	2.23	11.09	1.05	1.71	426.67	Eddy, UF
Kannur	11.06.09	100	64.05	1180	29.08	35.47	4.01	22.37	23.35	6.09	225.87	3.39	0.88	385	
Kannur	11.06.09	50	27.24	530	28.98	35.02	4.09	22.09	0.85	4.84	113.38	0.39	1.5	115	

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.5 *Rastrelliger kanagurta* larval retention areas: Environmental set up

Transect	Date	Depth (m)	Larval abundance (Nos.10 m^{-2})	SST (^oC)	SSS (psu)	S-DO (ml/L)	Density (Kgm^{-3})	Ekman drift ($cm\ s^{-1}$)	Wind Speed ms^{-1}	W^3 index ($m^3.s^{-3}$)	Chl-a ($mg.m^{-3}$)	MesoZP ($ml.m^{-3}$)	Cpd	Remarks
Trivandrum	31.5.2009	50	149	26.38	35.01	5.74	22.92	0.33	4.25	77.00	8.89	1.92	198.40	ED low
Trivandrum	2.6.2009	200	211	26.87	35.41	2.95	23.06	4.05	2.23	11.00	1.05	1.71	426.67	Eddy, ED low,
Trivandrum	1.6.2009	500	112	29.19	34.89	4.55	21.92	3.32	4.79	110.00	0.36	0.68	1,140.00	Eddy, Up F, ED low
Trivandrum	9.6.2010	100	377	26.45	34.92	4.63	22.83	1.84	4.39	85.00	4.31	0.67	344.83	Up F, ED Low
Kollam	3.6.2009	50	2,935	27.76	34.94	5.14	22.42	1.89	6.64	293.00	1.10	13.33	37.33	Eddy, Up F, ED Low
Kollam	14.6.2010	100	264	26.97	34.92	6.27	22.67	1.24	1.99	8.00	8.55	0.89	1,555.11	ED Low
Kannur	12.6.2009	200	386	29.59	35.72	4.04	22.41	2.88	4.43	87.00	0.65	1.13	1,170.00	ED Low
Cape	30.05.15	53	200	27.90	35.05	4.46	22.46	36.33	6.9	328.51	4.38	0.31	83.08	Up F

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.6. Details of *Encrasicholina devisi* spawning grounds and environmental set up

Transect	Date	Depth (m)	Distance from coast (Km)	Egg abd nos.10 m^{-2})	SST (^oC)	SSS (psu)	S--DO (ml/L)	Density (Kgm^{-3})	Ekman drift ($cm\ s^{-1}$)	Wind Speed ms^{-1}	W3 index ($m^3.s^{-3}$)	Chl-a ($mg.m^{-3}$)	MesoZP ($ml.m^{-3}$)	Cpd
Kannur	11.06.09	50	27.24	530	28.98	35.02	4.09	22.09	0.85	4.84	113.38	0.34	1.5	115
Trivandrum	28.05.15	35	6.11	435	28.09	34.57	2.86	22.04	0.28	5.5	166.3	2.86	0.75	280
Valappad	03.06.15	32	14.72	98	30.6	34.73	4.02	21.31	5.19	3.7	50.65	0.23	2.55	2094.55

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.7: *Encrasicholina devisi* larval retention areas: Environmental set up

Transect	Date	Depth (m)	Larval abundance (Nos.10 m^{-2})	SST (^oC)	SSS (psu)	S-DO (ml/L)	Density (Kgm^{-3})	Ekman drift ($cm\ s^{-1}$)	Wind Speed ms^{-1}	W3 index ($m^3.s^{-3}$)	Chl-a ($mg.m^{-3}$)	MesoZP ($ml.m^{-3}$)	Cpd	Remarks
Cape	31.05.09	50	117	26.21	34.96	4.82	22.94	22.94	5.26	145.53	9.79	1.80	236.00	Up F
Cape	30.05.09	100	110	27.03	34.89	4.68	22.63	0.93	6.03	219.26	6.48	3.82	2610.91	ED Low
Trivandrum	31.05.09	50	189	26.38	35.01	5.74	22.92	0.33	1.99	77	8.89	5.33	2524.00	Eddy, ED Low
Trivandrum	2.06.09	200	291	26.87	35.41	2.95	23.06	4.05	2.23	11	1.05	1.71	426.67	Eddy, ED Low
Trivandrum	1.06.09	500	805	29.19	34.89	4.55	21.92	3.32	4.79	110	0.36	0.68	1140.00	Eddy, Up F
Trivandrum	9.06.10	100	818	26.45	34.92	4.63	22.83	1.84	4.39	85	4.31	0.67	344.83	Up F, ED Low
Trivandrum	9.06.10	200	111	27.27	35.21	4.96	22.78	0.01	3.51	43	1.23	0.90	1348.65	Up F, ED Low
Trivandrum	28.05.15	203	549	30.68	33.85	4.66	20.63	14.49	5.1	132.65	4.67	0.44	262.22	River Plume
Kollam	3.06.09	500	268	29.63	35.56	3.99	22.27	11.69	3.85	57.07	0.59	13.33	37.33	Eddy
Kochi	13.06.09	200	124	28.89	35.07	4.27	22.15	6.42	4.48	89.92	0.63	1.43	141.71	
Kochi	19.06.10	50	166	28.77	33.85	4.27	21.28	0.99	2.33	12.65		1.50	2582.50	ED low, River Plume
Calicut	10.06.09	50	1123	28.86	35.03	3.99	22.13	1.09	4.82	111.98	0.36	0.53	36.89	ED Low
Calicut	3.07.10	30	559	28.18	33.69		21.09	26.05	8.09	529.48				River plume
Calicut	25.05.15	54	265	31.14	34.45	4.54	20.92	15.07	6.9	328.51	4.54	0.47	62.59	

Kannur	11.06.09	100	550	29.08	35.47	4.01	22.39	23.35	6.09	226	3.39	0.88	385.00	
Kannur	12.06.09	200	1712	29.59	35.72	4.04	22.41	2.88	4.43	87	0.65	1.13	1170.00	ED Low
Mangalore	29.06.09	100	112	28.77	35.30	3.92	22.37	0.00	1.14	1	0.95	1.13	1170.00	ED Low
Mangalore	24.05.15	52	152	31.26	34.73	4.43	21.09	3.289	4.2	74.09	4.43	0.53	26.13	
Goa	08.08.15	200	262	28.79	36.25		23.07	32.90	9.60	884.73				

RP-River Plume; UF-Upwelling Front, E-Mesoscale eddy, ED-Ekman Drift

Table 5.8 Results of Principal Component Analysis (PCA) of Phase-1 SM2015

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**4.4**	**2.34**	**1.68**	**0.815**	**0.617**
Cumulative% of variation explained	**40**	**61.3**	**76.5**	**83.9**	**89.5**
Variables					
Latitude (Lat)	-0.281	-0.368	0.277	-0.095	0.421
Temperature (Temp)	-0.443	-0.198	-0.055	0.077	0.103
Salinity (Sal)	0.196	-0.076	0.617	0.359	-0.09
Dissolved Oxygen (DO)	-0.347	0.166	0.03	0.514	0.023
Density (Den)	0.416	0.11	0.331	0.113	-0.129
Chlorophyll (Chl)	0.434	0.05	0.09	-0.065	0.199
Wind Speed (WS)	0.041	0.526	-0.08	-0.22	0.413
Ekman Drift (ED)	-0.012	0.489	-0.162	0.494	0.294
Distance from the coast (Dis)	-0.344	0.262	0.228	0.071	-0.51
Mesozooplankton Abd. (Mesozp)	0.194	-0.415	-0.182	0.493	0.274
Copepod Abd. (Cpd)	0.216	-0.142	-0.551	0.186	-0.393

Table 5.9 Results of Principal Component Analysis (PCA) of Phase-1 SM2009

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**3.99**	**1.98**	**1.31**	**1.12**	**0.813**
Cumulative% of variation explained	**36.2**	**54.3**	**66.1**	**76.4**	**83.7**
Variables					
Latitude (Lat)	0.385	-0.247	-0.035	0.121	0.024
Temperature (Temp)	0.455	0.178	0.023	-0.169	-0.168
Salinity (Sal)	0.098	0.108	-0.818	-0.057	-0.074
Dissolved Oxygen (DO)	-0.358	-0.035	0.097	-0.385	-0.25
Density (Den)	-0.399	-0.108	-0.47	0.124	0.11
Chlorophyll (Chl)	-0.447	-0.049	-0.095	0.048	-0.155
Wind Speed (WS)	-0.077	0.53	0.03	0.23	-0.488
Ekman Drift (ED)	-0.068	0.551	0.077	0.121	-0.163
Distance from the coast (Dis)	0.335	0.196	-0.283	-0.305	-0.019
Mesozooplankton Abd. (Mesozp)	-0.153	0.266	0.061	-0.729	0.317
Copepod Abd. (Cpd)	0.048	-0.433	-0.011	-0.309	-0.709

Table 5.10. Results of Principal Component Analysis (PCA) of Phase-2 SM2010

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**3.96**	**1.98**	**1.83**	**1.15**	**0.696**
Cumulative% of variation explained	**36**	**54**	**70.7**	**81.1**	**87.5**
Variables					
Latitude (Lat)	0.328	0.005	0.213	-0.421	-0.517
Temperature (Temp)	0.437	0	0.012	-0.089	0.031
Salinity (Sal)	0.177	-0.625	-0.055	0.179	0.058
Dissolved Oxygen (DO)	-0.142	-0.39	-0.081	-0.671	0.269
Density (Den)	-0.082	-0.652	-0.049	0.222	-0.101
Chlorophyll (Chl)	-0.441	0.13	-0.081	-0.098	0.33
Wind Speed (WS)	0.047	-0.046	0.67	0.278	0.126
Ekman Drift (ED)	-0.049	-0.066	0.675	-0.216	0.228
Distance from the coast (Dis)	0.341	0.073	-0.077	0.162	0.632
Mesozooplankton Abd. (Mesozp)	-0.385	-0.033	0.118	0.313	-0.262
Copepod Abd. (Cpd)	-0.424	-0.044	0.101	-0.157	-0.025

Table 5.11. Results of Principal Component Analysis (PCA) of Phase-3 SM2009

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**3.49**	**2.81**	**1.4**	**1**	**0.685**
Cumulative% of variation explained	**31.7**	**57.3**	**70.1**	**79.2**	**85.4**
Variables					
Latitude (Lat)	0.285	-0.198	-0.343	-0.201	0.257
Temperature (Temp)	0.485	0.061	0.113	0.172	-0.132
Salinity (Sal)	-0.307	0.347	0.178	0.425	-0.02
Dissolved Oxygen (DO)	0.198	-0.049	0.563	-0.275	-0.566
Density (Den)	-0.468	0.212	0.057	0.199	0.048
Chlorophyll (Chl)	-0.407	-0.037	0.149	-0.392	-0.16
Wind Speed (WS)	-0.174	-0.459	-0.072	0.184	-0.402
Ekman Drift (ED)	-0.015	-0.389	-0.296	0.509	-0.35
Distance from the coast (Dis)	0.325	0.122	0.391	0.424	0.184
Mesozooplankton Abd. (Mesozp)	-0.065	-0.443	0.421	0.084	0.339
Copepod Abd. (Cpd)	-0.159	-0.464	0.269	0.001	0.369

Table 5.12. Results of Principal Component Analysis (PCA) of Phase-3 SM2013

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**2.4**	**2.17**	**1.05**	**0.826**	**0.378**
Cumulative% of variation explained	**34.3**	**65.4**	**80.4**	**92.2**	**97.6**
Variables					
Latitude (Lat)	-0.216	-0.309	-0.145	0.886	0.08
Temperature (Temp)	-0.473	-0.403	0.125	-0.062	0.035
Salinity (Sal)	0.345	-0.502	0.394	-0.001	-0.03
Dissolved Oxygen (DO)	-0.479	-0.041	0.518	-0.201	0.498
Density (Den)	0.498	-0.354	0.346	0.023	-0.04
Chlorophyll (Chl)	0.318	0.454	0.24	0.32	0.603
Wind Speed (WS)	0.18	-0.396	-0.602	-0.26	0.615

Table 5.13 Results of Principal Component Analysis (PCA) of Phase-3 SM2015

Principle Components	PC1	PC2	PC3	PC4	PC5
Eigenvalues	**3.16**	**1.79**	**1.34**	**0.426**	**0.249**
Cumulative% of variation explained	**45.2**	**70.7**	**89.9**	**95.9**	**99.5**
Variables					
Latitude (Lat)	0.421	0.117	-0.538	-0.146	0.05
Temperature (Temp)	0.486	0.075	0.312	0.311	-0.534
Salinity (Sal)	0.081	-0.711	-0.082	0.202	-0.437
Density (Den)	-0.315	-0.565	-0.28	-0.122	0.084
Wind Speed (WS)	0.428	-0.307	0.2	0.413	0.715
Ekman Drift (ED)	-0.416	-0.027	0.568	0.091	0.042
Distance from the coast (Dis)	0.353	-0.246	0.407	-0.804	0.034

Chapter 6

Summary & Conclusion

Eggs and ontogeny of three species of small pelagic fishes, the oil sardine, Indian mackerel and the anchovy, *E.devisi* from the upwelling system of SEAS are described by dividing the study area into three distinct zones namely the South Zone (Cape to Kollam), the Central Zone (Kollam to Calicut) and the North Zone (Calicut to Goa). Eggs and larval abundance, egg & larval morphology, distributional patterns of eggs and larvae and correlations between larval abundance and environment are explained.

The study area extending between the Kerala-Goa coast (7^{o}N to 15.2^{o}N) was covered through systematic survey's involving 12 horizontal transects (shore to offshore) namely Cape (T_1), Trivandrum (T_2), Kollam (T_3), Alleppey (T_4), Kochi (T_5), Valappad (T_6),Calicut (T_7), Kannur (T_8), Mangalore (T_9), Bhatkal (T_{10}), Karwar (T_{11}) and Goa (T_{12}). Along each transect 6 depth stations (30m, 50m, 100m, 200m, 500, and 1000m) were chosen for the collection of eggs and larvae and associated environmental data. Study period extended from year 2009 to 2015 and collections were made exclusively on-board FORV.Sagar Sampada. Results are presented on the basis of analysis of 234 Bongo and few MPN collections.

Oil sardine, Anchovy and Indian mackerel spawn at around the same time, but at different spawning grounds. Oil sardine spawn

predominantly in upwelled waters close to the coast. Anchovy on the other hand prefer non-upwelling areas with low salinity as their spawning grounds and therefore exhibit a wide distributional range of eggs and larvae. Indian mackerels mostly spawn in offshore areas of open ocean upwelling or cold core eddy regions.

Oil sardine eggs from SEAS are spherical in shape, with size range between 1.06mm to 1.26mm diameters and have a single oil-globule. Indian mackerel have the smallest eggs (0.91mm to 0.98mm in diameter), are spherical in shape and with a single large oil-globule. The egg of the anchovy, *Encrasicholina devisi* are ellipsoidal in shape, have a length of 1mm to 1.06mm and are devoid of the oil-globule.

Newly hatched oil sardine larvae are transparent, slender, elongated and measure 3.3mm in length in field collections and between 2.865mm to 4.3mm in rearing experiments. The larvae are characterized by the presence of an ellipsoidal yolk-sac on the anterio-ventral side of the body, with the larval head bending over the yolk-sac. Eyes are not pigmented. Melanophores 24 pairs, on the dorsal side of the body. Anchovy larvae on hatching are slightly smaller in length (2.72mm) and resemble the sardine larvae except that they have 29 melanophores on the dorsal margin, a shorter gut and a conspicuous inflated gas bladder on the mid-gut. The newly hatched mackerel larvae, on the other hand are conspicuously smaller (1.48mm SL), have a curled shape, with a body broader than the other species and possess 18 melanophores on the ventral side.

In the rearing experiments conducted on-board, the daily growth rate of sardine larvae in the first few days was 1.12mm D^{-1} for the May spawned batch and 1.44mm D^{-1} for the August batch. This may be due to

the fact the annual spawning stock of oil sardine comprises of multi-age groups with the May spawning cohort dominated by the first time spawners (lay smaller sized eggs) whereas higher age groups dominate the latter stages of the peak spawning season (lay comparatively bigger sized eggs). However, in the case of *R.kanagurta* the reverse of this pattern occur with the May-June batch showing faster growth rates (0.339mm D^{-1}) as compared to the July-August batch (0.204mm D^{-1}).

Growth rates of larvae from the field collections (newly hatched to juveniles) estimated using length frequency mode progression indicate growth rates of 0.995mm D^{-1} for the May-June batch of larvae and 0.726mm D^{-1} for the July batch. The faster growth rate in May-June batch larvae may be due to the availability of pico and nanoplanktons (start of upwelling season) in the right size class preferred by sardine larvae, whereas by July the phytoplankton is dominated by diatoms.

Larval growth rates of *E.devisi* in field conditions were estimated as 0.61mm D^{-1} for the May batch and 0.57mm D^{-1} for the July batch. The difference in growth rates of larvae from the May and July spawning stocks is insignificant. This indicates to the adaptability of anchovy larvae to exist and grow in wide environmental set ups and their ability to feed on a wide range of food items.

In mackerel larvae, growth rates were the lowest being 0.34mm D^{-1} for the May-June batch and 0.264mm D^{-1} for the July-August batch. However on hatching the larvae from both the batches were almost of the same length (1.5mm & 1.54mm). Therefore the difference in larval growth rates of the two batches appears to be due to the reduced availability of food to the July-August batch of larvae with the dispersal of food items on intensification of upwelling and the limitations of mackerel larvae to

search for food as they have poor swimming and manoeuvring capabilities (less elongated and broad body).

Larval growth rates in oil-sardine is much faster (1.12mm D^{-1}) compared to *E. devisi* (0.605mm D^{-1}) and *R.kanagurta* (0.339mm D^{-1}). The body shape (long, slender), good swimming and manoeuvring abilities, choice of coastal upwelled waters as nursery grounds etc., may be the contributing factors for the fast growth rates observed in sardine larvae. The relatively slow growth of anchovy larvae may be due to their choice of non-upwelled waters, a trade-off to gain maximum distributional range. Despite having a large mouth gape which permit mackerel larvae to feed on a wide range of food items, the slow growth rate in mackerel larvae may perhaps be due to their body shape which promotes weight increments than length increments. However, in the present study length-weight relations were not undertaken to substantiate this.

Swimming and manoeuvring abilities of fish larvae are dependent on body depth (BD), whereas mouth gape (LJL) determine the maximum size of prey the larvae can ingest. The BD to SL is less in oil sardines and anchovies (0.09X and 0.089X) and high (0.276X) in Indian mackerel which implies better swimming and manoeuvring capabilities for the first two species, compared to Indian mackerels. Similarly the ratio between LJL & SL gives an indication of the mouth gape of the species and its ability to ingest bigger sized food items. The ratio is highest in mackerels (0.099X) compared to anchovies (0.0848X) and oil sardines (0.0853X). This implies that mackerel larvae can feed on a wide size-range of food items.

During the SM upwelling season in SEAS, numerical abundance of fish eggs were maximum in the SZ (68.91%), followed by the CZ

(23.9%) and NZ (7.18%), which implies that most fish species prefer the SZ over the other two zones for the purpose of spawning. Though wide inter-annual variations in egg abundance are evident, the general trend indicates maximum abundance of eggs in the SZ during phase-1 & 2 of SM corresponding to the onset and peak phase of the upwelling season in SEAS. It is well established that the upwelling process in SEAS is initiated in the SZ and advances northwards as the season progresses. The observed high abundance of eggs is therefore consistent with the overall environmental set up of the SZ that may perhaps stimulate spawning in most fish species.

Unlike phase-1 & 2, the wane phase of SM upwelling (phase-3) do not show any consistent pattern in egg distribution and abundance. In the year 2009, NZ dominated in the abundance of fish eggs, whereas in 2013 and 2015 egg abundance was high in the CZ.

In the 234 Bongo collections made over the seven year sampling period (2009 to 2015), a total of 58500 sardine eggs were obtained from the 30m isobaths of the CZ (6645 eggs) & NZ (51855 eggs). Sardine eggs were totally absent from the 50m isobaths onwards, which indicates that oil-sardine is predominantly a coastal spawning species.

Oil-sardine eggs were less represented in the collections from SZ. Nevertheless, during phase-1 of SM, sardine larvae were abundant in the 30m (279 larvae), 50m (40445 larvae) & 100m (7789 larvae) isobaths of the SZ, which implies that they may spawn in the SZ also. This assumption was proved right, in a subsequent cruise (FORV SS- 360 in May 2017) wherein one Bongo full of sardine eggs (83848 eggs.$10m^{-2}$) was collected from the 50m depth station off Trivandrum (8°21.43'N; 76°51.84'E) on the 25th of May, setting an exception to the general trend

observed in the previous years. The total absence of sardine eggs in our collections from SZ during the present study period, may be due to earlier spawning of sardines in the SZ (ie; before phase-1 period of 15 May to 15 June).

Oil sardine eggs were obtained from the CZ during phase-1 of year 2009 (666 egg.10m^{-2}) and phase-3 of years 2009 (108 eggs.10m^{-2}) and 2015 (5871 eggs.10m^{-2}). In the NZ sardine eggs were detected in phase-3 of year 2009 (215 eggs.10m^{-2}) and 2015 (51640 eggs.10m^{-2}).

Though the present data set do not cover shallow coastal waters below 30m isobaths (due to inherent operational limitations of the vessel FORV-SS) where maximum oil-sardine egg abundance is expected, from the available data it appears that oil-sardines in general prefers the onset phase of SM upwelling for peak spawning which appears to be prior to 15 May and the starting of phase-1 SM in the SZ and phase-1 SM (15 May to 14 June) in the CZ and phase-3 SM in the NZ. In the SZ, 0.5% larvae were found in the 30 m isobath, 79% in the 50m, 15.3% in the 100, 2.4% in the 200m and 2.8% in the 500m isobaths. For the CZ larval distribution was nil for 30m, 56.4% in the 100m, 21.8% each for the 100 & 200m isobaths and nil in the 500m isobaths. In the NZ 26.4% larvae were in the 30m, 67% in the 50m, 4.9% in the 100m, 1.4% in the 200m and only 0.3% was found in the 500m depth strata. These results are consistent with the strength of offshore transport, as explained in chapter-6.

R.kanagurta eggs were obtained only during phase-1 of year 2009, from the 50m station (975 eggs.10m^{-2}) and the 200m station (255 eggs.10m^{-2}) off Trivandrum (total of 1230 eggs.10m^{-2}) on 2.6.2009. Bongo collections from off Kannur on 11.6.2009 from the 50m station (530 eggs.10m^{-2}) and the 100m station (1180 eggs.10m^{-2}) also yielded good

quantities (1710 eggs.10m^{-2}) of mackerel eggs. Despite reasonably good sampling efforts, mackerel eggs were not found in the 30m stations throughout the study area, which suggest that the species spawn in the 50m to the 200m isobaths.

SZ accounted for 41.8% of egg and 93.3% of larval abundance and the NZ had 58.6% egg and 6.3% larval abundance during phase-1 of the study period. Mackerel eggs were conspicuously absent in the CZ and the occurrence of larvae was negligible (0.4%) during all the 3 phases of the study period. This indicates that mackerel avoid CZ for spawning and as nursery grounds.

For the anchovy, *E.devisi* though eggs were obtained only in the phase-1 collections from SZ (435 eggs.10m^{-2}), CZ (98 eggs.10m^{-2}) and NZ (530 eggs.10m^{-2}), their larval distribution is found to be spread across all the 3 zones (40.8% in SZ, 26.9% in CZ and 32.3% in NZ) in all the 3 phases of SM upwelling season, implying that they probably spawn throughout the SEAS during all phases of SM.

The three coastal pelagic species account for nearly 70% of the total larval abundance (72734 nos.10m^{-2}) of SEAS during SM season with oil sardine forming 55.5%, *E.devisi* 7.2% and Indian mackerel 7.05%. Total larval abundance in the 3 zones of SEAS did not show any positive correlation with egg abundance. This suggests that the eggs and larvae are widely dispersed by surface current drifts and/or through turbulence.

As expected, the larval abundance showed zonal and phase-wise variations that were in line with the appearance and northward progression of SM upwelling. In phase-1, the SZ accounted for 90.9% of larval abundance (107655 ind.10m^{-2}), followed by the NZ (4.9%) and the

CZ (4.2%). During phase-2, the CZ showed 60.8% larval abundance with the SZ & NZ contributing to 20.6% & 18.6% of the total larval abundance. Phase-3 of the SM season was marked by high abundance of larvae in the NZ (60.6% of the total of 20249 ind.10m^{-2}) followed by the CZ (23.8%) and SZ (15.6%). Larval abundance decreased from the coast (60.18%) to the shelf (34.46%) and slope (5.36%) areas. High larval abundance in the SZ during Phase-1, in the CZ during phase-2 and in NZ during phase-3 is consistent with the northward progression of SM upwelling.

Although *S.longiceps*, *E.devisi* and *R.kanagurta* occupy the same habitat for spawning and as nursery grounds, subtle variations in spawning grounds, peak spawning period and location of nursery grounds are expected to avoid interspecific competitions amongst these species for food and space. *E.devisi* appears to spawn in non-upwelling areas throughout the study area much earlier (Mid-April to Mid-May) than the other two species with its spawning and nursery grounds distributed all along the coastal and offshore of SEAS. On the other hand, peak spawning period in *R.kanagurta* corresponds with the onset phase of SM upwelling (mid-May to mid-June) with major spawning grounds located in upwelling areas, fronts or cold-core eddy regions beyond the 50m isobaths, which help avoid direct competition with *E. devisi* larvae. In *S.longiceps*, spawning is rather protracted with peak spawning in SZ prior to phase-1, during phase-1 in the CZ and during phase-3 in the NZ. The preferred spawning and nursery grounds correspond with coastal upwelling areas, fronts which help them reduce competition with the other two species.

The preference of oil sardine on coastal upwelled waters; *R.kanagurta* on offshore upwelling areas or cold core eddy regions as their

spawning and nursery grounds and the choice of *E.devisi* on non-upwelled low saline waters near shore and offshore are confirmed from the results of PCA carried out to establish correlations in larval abundance with several environmental variables. The ability for resource portioning amongst the larvae perhaps explain the success of small pelagic fishes in the upwelling systems world over.

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Appendices

Publications

1. Sree Renjima G, Sanjeevan VN, Smitha BR, Lalithambika Devi CB & Sudhakar M. 2017. Early developmental stages of the Indian mackerel *Rastrelliger kanagurta* (Cuvier) along the Kerala - Mangalore coast of South Eastern Arabian Sea. *JMBAI* 58(2): 68-80.

2. Padmakumar K.B, G. SreeRenjima, C. L. Fanimol, N. R. Menon and V.N.Sanjeevan (2010). Preponderance of heterotrophic *Noctiluca scintillans* during a multi-species diatom bloom along the Southwest coast of India. *International Journal of Oceans and Oceanography* Vol. 4 (1): 55-63

3. Padmakumar K.B, B.R. Smitha, Lathika Cicily Thomas, C. L. Fanimol, G. SreeRenjima, N. R. Menon and V. N. Sanjeevan (2010). Blooms of *Trichodesmium erythraeum* in the South Eastern Arabian Sea during the onset of 2009 Summer Monsoon. *Ocean Science Journal*, Vol. 45 (3): 151-157.