Fish larval transport in the coastal waters through ecological modelling

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by

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To my teachers who moulded my academic zeal

Statement

As required under the University ordinance 0.19.8.(vi), I state that this thesis entitled *Fish larval transport in the coastal waters through ecological modelling* is my original contribution, and it has not been submitted on any previous occasion.

The literature related to the problem investigated has been cited. Due acknowledgements have been made wherever facilities and suggestions have been availed of.

Grinson George

National Institute of Oceanography
February 2011

Certificate

This is to certify that the thesis entitled *Fish larval transport in the coastal waters through ecological modelling* , submitted by Grinson George to Goa University for the degree of Doctor of Philosophy, is based on his original studies carried out under my supervision. The thesis or any part thereof has not been previously submitted for any other degree or diploma in any university or institution.

P. Vethamony

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All the corrections suggested by the referees have been incorporated.

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Abstract

The coastal waters of India are rich in diverse marine larval population, and fish larvae form the major commercial group. Larval phase of marine organisms is very important in deciding their future stock and abundance. There are a few obnoxious bioinvasive barnacle larvae, which spread in the coastal waters and form a biofouling agent disturbing harbour, jetties, navigation and recreational activities. Larvae of marine organisms are passively drifted along with the ambient currents from their spawning sites to nursery areas where they develop into juveniles. It is imperative to protect such nursery areas of economically important species, and restrict the areas of dispersion of larvae in the case of obnoxious or bio-invasive species. There are several techniques employed for determining the larval transport in the marine environment. They include extensive field surveys, screening the larval samples using molecular tools (to distinguish endemic larvae spreading to different locations from their natal sites), attaching markers/ tags and releasing larvae (to find out their extent of retention/ dispersion), quantifying physical parameters like winds, tides and currents to relate the possible passive transport of larval biomass and numerical model as a tool for simulating the larval transport processes. Numerical simulations give a synoptic scale information for a larger area on the larval transport of marine organisms, compared to other techniques, which provide point data. Further, numerical models once validated for a region can act as a decision support system. Hence, the present study is carried out using numerical modelling techniques, utilising measured / sampled data.

There is a greater influence of environmental parameters deciding the biology of marine larvae, and it is possible to track the actively swimming juveniles based on their ambient conditions, especially food. Therefore, this thesis examines the influence of ambient food factors in sardine (a major pelagic fish in the western coastal waters of India) larval survival. The aggregation response and inter-annual variability in sardine is explored using satellite-derived chlorophyll. Further, the larval transport of fish and shell-fish in three unique marine ecosystems along the west coast of India is carried out with the help of numerical modelling. With this background, the objectives of the study are framed as follows:

(i) to find out the influence of environmental parameters on the biology of the given ecosystem

(ii) to track larval transport and biological abundance in relation to environmental variables

(iii) to compare biological abundance and fish larval transport in three different marine ecosystems, namely, the Gulf of Kachchh (a semi-enclosed basin), Mandovi-Zuari (major estuarine system of Goa), and off Mangalore (an open coast with seasonal variability)

Introduction to this thesis describes background of the work, followed by thesis outline, literature review, objectives and scope of the present work and regional oceanography and ecology. The literature review covers the importance of larval phase in marine organisms, methodologies adopted and larval transport (in corals, echinoderms, shell-fish and fish). Data collected and analyzed is described along with a complete description on modelling of hydrodynamics and larval transport. The data includes satellite derived chlorophyll, fish landing and wind, tide and current measurements carried out in the Gulf of Kachchh (GoK), Goa and Mangalore. Numerical simulation includes a description on model domain, grid size, time step and length of simulation, bathymetry, calibration, sensitivity analysis and validation experiments. Validated results are used for describing the larval transport.

The survival, migration and aggregation pattern of Indian oil sardine larvae has been studied using satellite-derived chlorophyll. The biology, migratory pattern of sardine and the importance of satellite chlorophyll in sardine fisheries, relationship of sardine and chlorophyll variability, seasonal appearance of sardine in association with the progressing or receeding chlorophyll and the response of chlorophyll during bloom initiation month with the fishery are discussed. Monthly averaged surface phytoplankton biomass has been estimated along the waters of southwest coast of India from the shoreline upto 200 m isobath for ten years (1997-2007) using *SeaWiFS* ocean colour data. This estimation is compared with the biological calendar of Indian oil sardine. The average chlorophyll-a for the bloom initiation month (1998-2006) matches very well with sardine landings. The results imply that the concentration of chlorophyll-a during the bloom initiation month can be used to assess the quantum of fish that recruit into the population. Finer scale spatial variations in the chlorophyll along the coastal waters help in deciphering the migratory pattern of sardines during their active breeding phase. This study shows that *39 % variability* in fish landings is related to availability of chlorophyll-a during the bloom initiation month. But, larval abundance in a region depends not only on the biological processes, but also on the physical processes (air-sea interactions and processes driven by tides and currents). In this context, larval transport is modelled in three different regions (Gulf of Kachchh, Goa and off Mangalore) along the west coast of India to explore the significance of physical processes in the larvae abundance. The results reveal different patterns of aggregation response in temporal and spatial scales.

Current pattern/ circulation of an area influences the larval transport processes for passive swimmers, like most of the marine larvae immediately after their spawning. So it is important to have an understanding of the current pattern for studying the larval dipsersion processes from spawning sites. In the present study, the focus is on regional oceanographic processes which influence the larval transport of fishes and shell-fishes. For this purpose, a two dimensional hydrodynamic model is used to generate flow pattern of select coastal regions. Simulated currents are validated with measured currents (speed and direction), and the match is very good (correlation coefficient is $\geq$ 0.84). In the GoK, tidal circulation controls the hydrodynamics. Even though currents along the Goa region (Mandovi-Zuari estuary) and Mangalore coastal waters are tide dominated seasonal winds have a significant role in controlling the hydrodynamics.

Further, larval transport in these different marine ecosystems has been studied utilizing the hydrodynamic model results as input. During numerical simulations, fish and barnacle larvae are defined as particles with a specific mass based on observations and released at specific spawning sites. Lagrangian random-walk technique is used in the model to track the movement of the particles released. For the GoK, six spawning sites have been identified for larval release based on field surveys and particle trajectory pattern. The model results and field observations indicate a larval aggregation towards the southern Gulf. Experimental trawling in the gulf several years confirms the better abundance of fish in the southern Gulf. In the numerical simulations it is evident that 10-20% of the larval particles released from spawning sites exited from the Gulf along the northern boundary. Thus, the numerical simulations carried out in the GoK reiterates the fact that fish larval abundance is higher in the southern gulf. Therefore, proper demarcation of the nursery areas of fishes based on the model data may be an effective management measure to sustain the local fishery in the Gulf. Similarly, release of fish larvae from the three major spawning areas off Mangalore (Malpe, Mulki and Netravati) indicates aggregation of fish larvae at Mangalore fishing ground. Thus, it could be inferred that better fish abundance in the traditional fishing ground off Mangalore is primarily due to the current pattern which supports larval accumulation. Based on the numerical simulation results it is possible to improve the fishery management measures in the GoK and Mangalore coastal regions.

For the Goa region, distribution and abundance pattern of a bioinvasive barnacle, *Balanus amphiprite* is studied with the help of numerical modelling and observations. For studying the coastal dispersal of barnacle larvae eight spawning sites are selected based on an exploratory survey. The results indicate that the barnacle species is a part of a well mixed population, and there is a seasonal pattern of recruitment in their stock in Mandovi-Zuari estuary from different spawning sites along the coast. The dispersal distances varied from a few kilometers to 78 km stretch in the study domain. Field observations indicate that there is higher abundance of larvae in the estuary during October. The abundance significantly differed between all the three sampling periods (Analysis of Variance $(ANOVA): p \leq 0.0005$). There was an hourly variation in the larval abundance during May 2007 and October 2007 samplings. Further, the naupliar density increased with the tidal amplitude. Numerical simulations and wind data support these observations as the larvae tend to move into the estuary from open coastal waters with the flood currents. During northeast monsoon season, the mouth of the Mandovi-Zuari estuarine system is more exposed to northeast winds, and hence, a net offshore particle transport has been observed for the larvae at Singuirim and Dona Paula. Major amount of particles has been settled along the coastal belt south of Bogmalo for the spawning locations southward from Singuirim. The magnitude of southward spread of particles is in the increasing order from Arambol to Galgibagh during pre-monsoon season. However, the quantum of particles reaching the sampling point at Zuari estuary is in the increasing order from spawning locations at Anjuna, Singuirim and Arambol. During the study period it was observed that in the first half of October, there existed southwest winds with low magnitude and in the second half, northeast winds prevailed due to the onset of northeast monsoon. Therefore, in October dispersal of particle occured northward predominantly in the first half and reversed later in the second half. The numerical simulation data thus indicate that it may be resorted for the management of bioinvasive species like barnacles. In areas like ports and harbours, where ballast water release from vessels also contributes to the larval release, the ideal sites for ballast water release can be effectively managed based on the numerical simulations for the region.

Finally, it could be inferred from the study that ambient environmental parameters and food are major factors for larval survival and transport. This study further indicates that the chlorophyll abundance in the dwelling habitats of sardine at the initiation of their active breeding phase acts like a precursor of their annual biomass. In the case of passive swimmers and fish larvae numerical modelling is an effective tool in explaining the larval transport processes. There are initiatives globally to model the larval transport of marine organisms, and the present study is an attempt in that direction to explore the larval transport processes in the western coastal waters of India. Sparse reports and data sets on early life history stages of the marine organisms is a major lacunae in the study. This emphasizes the importance of generating long term datasets for the larvae of marine organisms in the Indian coastal waters. The future scope for this study is to improve the numerical model by incorporating the biological variables like prey-predation, food abundance and natural mortality. This can be achieved by carrying out the simulations for different regions and comparing them with longer time series data set. Remote Sensing and Geographical Information System (RS-GIS) can be largely used for demarcating potentially rich larval nursery areas based on modelling and observations. This can be a useful decision support system for the managers of fishery. Similarly, the release point of ballast waters and regulations for controlling the spread of obnoxious species like barnacles can also be identified. This present work suggests the relevance of applying remote-sensing and numerical model data as a surrogate for biological data sets in deriving scientific conclusions for management of marine ecosystems.

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Chapter 1

Introduction

1.1 Background

Fisheries form one of the means of sustenance for the coastal rural population in India [Thomson, 2009]. The major share of fish landing in India comes from the west coast. The nursery areas for fish along the west coast are located in the unique marine ecosystems consisting of coral reefs (*e.g.* the Gulf of Kachchh (GoK)) and mangroves (*e.g.* major estuarine areas). For effective management of these nursery areas along the coast, regulations are enforced in the form of closed areas and seasons [Singh, 1994]. The concept of closed area is followed by creating Marine National Parks and Marine Sanctuaries (*e.g.* GoK) at some ecologically relevant sites consisting of reefs and mangroves. These areas are closed for fishing on the belief that ecologically sensitive areas form nursery for most of the fishes. But, there are conflicting issues with respect to this concept [Singh, 1994]. Demarcating areas of aggregation of fish larvae will be helpful in rightly deciding a closed area. In case of obnoxious species like certain bio-fouling shell-fishes and barnacles, the extent of bio-invasion is relevant in taking management measures near harbour areas, where ballast water forms a means of transport for barnacles. Hence, we need to understand the mechanisms underlined in the fish or shell-fish larval distribution, both spatially and temporally.

There are various physical (driven by winds, tides and currents) and biological processes controlling the fisheries in an ecosystem [Dickey, 1990]. Seasonally changing monsoon is the major physical forcing which controls the biological abundance and fisheries along the west coast of India. There are excellent reports from this region not only on the variability of monsoon winds but also on their oceanographic and biological consequences in relationship to fisheries [Longhurst and Wooster, 1990]. However, these seasonal changes in monsoon, reflecting in the abundance on fish, were not examined as a trophic response to the reproductive cycle of fishes [Madhupratap et al., 1994]. This suspected trophic link for sardine fisheries forms part of the present study by exploring the remotely sensed chlorophyll as a putative trophic link to explain the survival of sardine larvae, their migration and aggregation pattern.

Fish larvae show variability in their abundance due to factors other than the monsoon driven seasonal trophic conditions. It is possible to model the larval transport and its bionomics through ecological models (hydrodynamics coupled with ecosystem). Various efforts were done in the Indian coastal waters to predict the abundance of fish landings with accuracy so that better management of capture fisheries could be done [Srinath, 1997; Sathianandan, 2002; Grinson George, 2002]. But, this was not sufficient enough to enforce a fishery management measure like closed area or season as these studies reveal only a cyclical trend in the fish landing data. The motivation for the present study is derived from the work of researchers such as Sammarco and Andrews [1988, 1989]; Pineda [2000]; Paris et al. [2005] and Cowen et al. [2006], who worked on numerical-models globally incorporating ambient conditions influencing fish larval transport to demarcate zones of larval aggregation.

Fish larvae are icthyo-plankton with no or less swimming ability. A proper information on hydrodynamics will improve our understanding of fish larval transport and their aggregation pattern along the coast. There are distinct regions along the west coast of India which show the presence of mangroves and abundance of fish larvae. These include semi-enclosed basins like the GoK and Gulf of Kambhat, estuaries such as Mandovi-Zuari, Netravati, Vembanad and Ashtamudi and dynamic areas where the coastal stretch is least obstructed (for *e.g.* open coast such as Mangalore). Numerical modelling provides an opportunity to reproduce the flow patterns at desired coastal regions and helps to study the fish/shell-fish larval transport during specific periods.

The present study is an effort to explain the mechanism of fish and shell-fish larval transport along the west coast of India (WCI) by coastal oceanographic processes using measurements and modelling. Since larvae remain planktonic during its initial phase of development, simulation and quantification of flow patterns prevailing along the coast for different seasons will apparently elucidate the possible larval spread from major spawning sites. Therefore, the following regions have been selected to study larval transport through numerical modelling:

(i) the GoK- a semi enclosed basin off Gujarat coast,

(ii) the Mandovi-Zuari estuarine system off Goa and

(iii) the Mangalore-Malpe stretch, an open region off Karnataka coast.

The modelling results were verified using measured and published data available for select locations.

1.2 Literature review

Fish and shell-fish larval transport is a multi-disciplinary subject. Various authors tried to explain the dispersion of larvae in aquatic environment [Cowen et al., 2000] using different tools. They attempted to describe larval transport based on the nature of their study, uniqueness of the area as well as species [Pineda, 2000; Paris et al., 2005; Cowen et al., 2006]. In this review, effort is taken to describe the larval dispersal, the factors influencing their dispersal, the methodologies adopted for describing dispersal pattern and the relevance of bio-physical link between various aquatic species.

1.2.1 Importance of larval phase of marine organisms

The life cycles of most marine organisms include a planktonic larval phase, usually lasting from weeks to months [Brothers et al., 1983; Moser and Boehlert, 1991]. Larval phase is important in marine ecology as marine invertebrates and fishes have a life cycle involving a demersal/nektonic adult and a Pelagic Larval Duration (PLD) phase or pelagic eggs which could be transported to long distances [Grosberg and Levitan, 1992]. There are four major reasons suggested for this PLD phase [Swearer et al., 2002]:

(i) A long PLD phase can help a species to break its parasite cycles: Larvae of some species metamorphose in response to chemical cues associated with a particular hostile species [Hadfield and Scheuer, 1985; Lambert et al., 1997]. In the absence of specific environmental cues, larvae postpone their metamorphosis and prolong larval life [Pechenik, 1990; Morgan, 1995].

(ii) Pelagic larvae avoid predators: Lengthy PLD phase and low probability of successful recruitment leads to larval release in huge numbers so that the chances increase for the survival of at least one larva [Thorson, 1950; Roughgarden et al., 1985; Caley et al., 1996]. However, studies on larval behaviour and ecology show that this is not true always [Kingsford et al., 2002]. Larvae are small in size and plentiful, and many animals take advantage of this food source. Some larvae have direct defense like large spines and other protective structures [Morgan, 1989]. Some larvae avoid predators by simply sinking when they are approached by a predator and certain larvae are nocturnal undertaking diel vertical migrations, as most larvivorous fishes are visual predators and need light to hunt. Marine larvae (and other zooplankton) can significantly decrease their risk of predation by withdrawing to areas of low light during the day [Zaret and Suffern, 1976]. In reverse tidal vertical migrations, larvae use the tidal cycle and coastal flow pattern to aid their departure to the ocean [Cronin and Forward-Jr., 1979; Tankersley and Forward-Jr., 1994; Zeng and Naylor, 1996; Di-Bacco et al., 2001].

(iii) Larvae have the potential to disperse long distances, invade new area, and move away from congested or incompatible location: Sluggish demersal marine organisms like barnacles, tunicates, mussels and crabs need some mechanism to shift their juveniles into new territory since they cannot traverse long distances as adults. These species have relatively long PLD phase of the order of weeks or months [Brothers et al., 1983]. During the PLD phase, larvae feed, grow and undergo stages of development. Some larvae are able to delay their final metamorphosis for a few days or weeks and some species cannot delay it [Gebauer et al., 2004]. If these larvae metamorphose too far from a suitable settlement site, they perish. Such species exhibit swimming rhythms of reverse tidal vertical migration to aid in their transport away from their hatching site, the same species can exhibit tidal vertical migrations to re-enter the estuary when they metamorphose and are competent to settle

[Christy and Morgan, 1998]. Many larvae become more tactile, clinging to larger objects than themselves. These objects along with the larvae can be transported towards shore due to oceanographic forces such as internal waves, which carry the floating debris shoreward regardless of the prevailing currents [Alan, 1985]. If they are able to successfully return to shore, settlers encounter a new suite of problems concerning their actual settlement and successful recruitment into the population. Space is a limiting factor for sessile invertebrates on rocky shores, and larvae might not find any open habitat. Additionally, settlers must be wary of adult filter feeders, which usually cover the rocks at settlement sites and eat particles similar to the size of larvae. Settlers must also avoid becoming stranded out of water by waves, and must select a settlement site at the proper tidal height to prevent desiccation and avoid competition and predation. To overcome many of these difficulties, some species rely on chemical cues to assist them in selecting an appropriate settlement site. These cues are usually emitted by adult conspecifics, but some species cue on specific bacterial mats or other qualities of the substrate [Crisp and Meadows, 1962; Pawlik, 1986].

(iv) Dissimilar food source of larvae may decrease competition between adults: Fish larvae are characterized by digestive systems and diets that differ from adults [Govoni et al., 1986]. Most barnacles molt through six naupliar stages before molting to a ciprid, the stage at which they seek an appropriate settlement substrate. This allows the larvae to use different food resources than the adults and gives them time to disperse.

1.2.2 Methodologies adopted to explain larval transport

While reviewing the literature, it was observed that researchers have used several techniques to resolve the larval transport processes. These observations helped in broadly categorizing these approaches into five methodologies, and these are described below:

(i) Field surveys to determine the pattern and extent of larval transport: Larval fish composition and abundance were determined based on field sampling at different parts of the world like Eastern Australia [Smith and Suthers, 1999], the Agulhas Current off South Africa [Beckley and Ballegooyen, 1992], the Western Irish Sea [Dickey-Collas et al., 1996], the English Channel [Giroche et al., 1999], south-western Africa [Oliver and Shelton, 1993], Peru [Velez et al., 2005], California Current [Loeb et al., 1983] and Canary Islands [Rodriguez et al., 2004]. Fish larval samples from International Indian Ocean Expedition (IIOE) [Peter, 1967] form the major larval data set for the Indian Ocean region.

(ii) Biotechnological approach to determine larval transport: The production of monoclonal antibodies for use as probes in the identification of northern Australian crown-of-thorns starfish *(Acanthaster planci)* and commercial prawn larvae [Feller, 1986; Hanna et al., 1994] is a manner in which biotechnological applications also made a foray into larval transport. A major difficulty experienced in marine ecological studies is an inability to distinguish between species at early larval stages, especially among crustacean and soft-bodied in-vertebrate larvae. The larvae of penaeid prawns and crown-of-thorns starfish are no exception, and as a consequence, studies of larval dispersion and recruitment into adult populations are difficult. An approach to this problem has been to produce monoclonal antibodies against preserved specimens of particular species and then select, through screening a range of different larvae, those that show species-specially.

(iii) Marker assissted sampling design: Twenty-four fishes fitted with 300 $k.Hz$ transponding acoustic tags were tracked by sector-scanning sonar in the southern North Sea for periods up to 52 h and over distances up to 72 km [Arnold et al., 1994]. Jones et al. [1999] and Swearer et al. [1999] found that a proportion of reef fish larvae was returning to their natal reef, after their maturation in the water column, with the help of markers. They found higher than expected (approximately 60%) self-recruitment in these populations, using variations of a typical mark, release, recapture sampling design. These studies were the first to provide conclusive evidence of self-recruitment in a species with the potential to disperse far from its natal site, and laid the groundwork for numerous future studies [Levin, 2006].

(iv) Larval transport as a manifestation of bio-physical processes: Different physical oceanographic processess influence the distribution of larval fish on a variety of scales, ranging from a few meters to thousands of kilometres, therefore, larval distribution is likely to be determined by their interaction with a number of concurrent features [Bruce et al., 2001; Hare et al., 2002]. The physical process relevant to the mixing and dispersion of marine organisms was explored with emphasis to the role of diffusion and related physical processes in dispersal and recruitment of marine populations [A.Okubo, 1994]. These processes include advection and diffusion occurring over a broad range of temporal and spatial scales of oceanic motion. Diffusion in the sea has customarily been treated as a stochastic process; but a chaos-induced or deterministic, diffusion, is necessary in order to improve our understanding of larval dispersal and recruitment. Tidal flows can move larvae passively in peak tidal velocities [Levin, 1990; Gross et al., 1992]. As the relevance of oceanographic features in explaining larval transport has been realised, numerous studies on these topics have been conducted, covering most of the world's coastal waters [Moser and Smith, 1993; Oliver and Shelton, 1993; Grothues and Cowen, 1999; Hare et al., 2001]. Physical processes not only affect the magnitude of the plankton biomass, but also the species composition [Huntsman et al., 1981], which may in turn affect larval fish feeding and survival [Lasker, 1975; Simpson, 1987].

(v) Numerical modelling as a tool to explain larval transport processes: Globally, various researchers have utilized different bio-physical numerical models to study the hydrodynamic pattern and further, the larval transport process. Numerical simulations give a synoptic scale data on the larval transport of marine organisms. Numerical experiments could be easily altered/ repeated for different scenarios by changing the variables acting on the larval transport, unlike other methods mentioned earlier. Other techniques could be a supporting tool in the quest for larval transport, providing point data. Further, numerical models once validated for a region can act as a decision support system. It works out to be a feasible option providing quick results without affecting the quality and level of interpretation.

The following subsection (1.2.3) describes in detail some of the major larval transport studies carried out globally using numerical models for different marine organisms.

1.2.3 Global studies on larval transport scenarios

This section illustrates larval transport of corals, echinoderms, shell fish and fish primarily through modelling.

(i) Corals-fertilization and dispersal pattern

Larval dispersal and recruitment processes in corals [Heyward and Negri, 2006], their analysis and synthesis [Sammarco, 1991] were done for Scleractinian corals, which reproduce via external fertilization and exhibit broader recruitment patterns than their brooding counterparts. Numerical simulations of coral dispersal [Galindo et al., 2006] have shown that particles occurring in different layers in shallow water produce different dispersal patterns. Normal trade winds in the central Great Barrier Reef region (15 $knots$) produce a wide dispersal pattern in eggs and larvae associated with the surface layer [Sammarco, 1991]. Coral recruits on a reef may be derived from both the near and far fields. Most recruits recorded in a large-scale experiment on the Great Barrier Reef (The Helix Experiment) [Sammarco and Andrews, 1988, 1989], were derived from the natal reef. The effects of recruitment strategies on coral larvae settlement distribution at Helix reef was also studied [Andrews and Gay, 1988]. A review on physical oceanographic aspects of the dispersal of coral spawn slicks [Pattiaratchi, 1994] reveals that the annual spawning of corals is limited to a brief period in which enormous quantities of eggs and larvae are injected into the reef systems. There are several factors affecting larval dispersion which is reported in a case study carried out in the central Great Barrier Reef [Parslow and Gabric, 1989].

(ii) Echinoderms with special emphasis on crown-of-thorns starfish

Black [1993] has studied dispersal on the Great Barrier Reef through multidisciplinary approach. Investigations of the dispersal of crown-of-thorns starfish *(Acan-*

thaster planci) larvae have provided new insights into the dynamics of larval dispersal of Australias Barrier Reef. Further, physical aspects of large-scale dispersal in the crown-of-thorns starfish *Acanthaster planci* [Dight et al., 1990] got into an in-depth analysis with numerical models.

(iii) Shell-fish dispersal

Various processes control the larval dispersal and post larval recruitment of penaeid prawns[Rothlisberg et al., 1983]. In the shallow Gulf of Carpentaria, tidal currents combine with the larval vertical migration to advect *Penaeus merguiensis* larvae up to 160 km over a 20 days period. Changes in tidal phase with respect to constant diurnal larval behaviour result in seasonal changes in advance direction, which are consistent with the observed spatial and seasonal recruitment patterns. In contrast tidal currents are not responsible for appreciable across-shelf advection of *P.plebejus* larvae on the open shelf of southeastern Australia. Similarly, transport processes affecting banana prawn post larvae in the estuaries of the Gulf of Carpentaria were explored [Heron et al., 1994]. Miyake et al. [2009] used a coupled particle-tracking and hydrodynamic model to simulate larval dispersal of large abalone *Haliotis discus discus, H.gigantea, H.madaka* in Sagami Bay, Japan . In the case of barnacles, large-scale offshore oceanographic processes operate first over higher abundances than the small scale nearshore processes that operate last over fewer individuals [Pineda, 1994, 2000]. In the present study, an attempt has been made to investigate the relevance of coastal processes in the distribution of barnacle larvae in the coastal waters off Goa.

(iv) Fish larval transport

Dispersal and advection of *Macruronus novaezealandiae (Gadiformes: Merlucciidae)* larvae off Tasmania with simulation of the effects of physical forcing on larval distribution was studied [Lyne and Thresher, 1994]. The hypothesis that passive drift alone of *Macruronus novaezealandiae* is sufficient to account for its distribution off the Tasmanian coast is tested with a Lagrangian model of larval drift. Dispersal of the larval stage of southern blue fin tuna *Thunnus maccoyii* in the East

Indian Ocean [Davis et al., 1991] is significant in the recruitment of fishery. Numerical modelling of fish eggs dispersion at the Patos Lagoon estuary in Brazil utilized a two dimensional hydrodynamic model-SIMSYS2D and a Lagrangian particle tracking model [Martins et al., 2007]. Since wind fields are influential in the strength and position of oceanographic features, climatic cycles like *El Nino* also influence larval fish transport and survival [Tsai et al., 1997; Cubillos and Arcos, 2002]. Fish larval transport is affected by a variety of physical and biological factors, operating over a wide range of temporal and spatial scales. However, the domain at which larval fish transport are studied will affect the processes that are ultimately deemed to be relevant. Potentially influential physical and biological factors may vary in time as well as space, therefore recent meteorological and oceanographic events, as well as regional seasonal and climatic cycles may also be significant.

1.3 Scope and limitation of larval transport studies in the Indian coastal waters

Successful fisheries management relies heavily on understanding population connectivity and dispersal distances, and these processes are driven by larvae. Dispersal and connectivity must also be considered when designing natural reserves, both on land and in the water; if populations are not self-recruiting, then solitary reserves may lose their species assemblages. Additionally, many invasive species are able to disperse long distances during an early life stage, such as seeds in land plants or larvae in marine invasives. Understanding the factors influencing their dispersal is the key to control their spread and managing pre-established populations. Through the continued study of the ecology of these microscopic creatures, we can understand better and manage more effectively the myriad populations in the sea. No attempt is made so far for studying larval transport of marine population in the coastal waters of India. The limitation for such study is the lack of continuous larval data set to compare with the model output.

1.4 Objectives of the present work

The present task is to study the fish larval transport along the WCI through ecological modelling. The influence of ambient food factors in fish larval survival and their aggregation response is explored using satellite chlorophyll for studying the interannual variability in sardine landing. A proper understanding of physical, biological and chemical processes in the region will help in studying larval transport along the coast. Taking into account of all these factors, the objectives of the study are framed as follows:

(i) to find out the influence of environmental parameters on the biology of the given ecosystem

(ii) to track larval transport and biological abundance in relation to environmental variables

(iii) to compare biological abundance and fish larval transport in three different marine ecosystems namely, the GoK (a semi-enclosed basin), Mandovi-Zuari (estuarine system of Goa), and Mangalore coastal region (an open coast with seasonal variability).

1.5 Study area

The study area lies along the WCI. The WCI comprises of the continental shelf of western India (5 to 25^oN) which widens from south to north, reaching about 300 km between 18^oN and 25^oN. The shelf break on this coast is approximately along the 200 m depth contour [Chandramohan et al., 1993; Shetye et al., 1991].

1.5.1 Regional oceanography

The currents along the WCI are primarily driven by semi-diurnal tides and seasonal wind systems prevailing over the region. Regional circulation responds both to local and remotely forced effects of the southwest (SW) and northeast (NE) monsoon winds. Onset of the SW monsoon occurs first in the south Indian Ocean in May or June, then spreads northward, and continues till October. From November to May, the coast is influenced by lighter, drier NE winds and some cooling and mixing of shelf water occurs. During this season, the cyclonic circulation of the Arabian Sea causes downwelling of isopleths near the coast. Sea breeze is also prevalent along the westcoast of India during this season. Coastal currents respond to local wind forcing with equatorward flow along the coast from February to September/ October and poleward during the rest of the year [Longhurst, 1998]. Broadly four seasons are prevalent in the region:

(i) pre monsoon from March to May

(ii) SW monsoon from June to September

(iii) post monsoon during October

(iv) NE monsoon from November to February

1.5.2 Regional ecology

Upwelling along the coastal waters is pronounced in the regional biological response of the waters. Nutrient levels are low during pre-upwelling period. The mixed layer is thin and subsurface low oxygen water starts to appear on the shelf. When Ekman upwelling begins the nutrient levels increase, the mixed layer becomes even thinner, and very low oxygen concentrations ($\leq$0.5 $ml.l^{-1}$) characterize shelf waters below the thermocline. The upwelling period is reflected with heavy algal blooms (8.0 $mg.chl.m^{-3}$) in response to the nutrient advection in the upwelled water and remineralization of nutrients locked in the mobile mudbanks. Blooms result in low water clarity (chlorophyll maximum $\leq$5 m; water column chlorophyll $\leq$200 $mg.m^{-3}$; Sechi disc, 2 or 3 m) with diatom cells at high concentrations of $<2.9*10^5 cells.l^{-1}$ [Shah, 1973]. Areas with strong seasonal diatom blooms may support a pelagic clupeid fish which depends almost entirely on medium to large diatoms for food, obtained by active filtration on gill-rakers: for example, *Brevoortia* in the western Atlantic, *Ethmalosa* in the eastern Atlantic, and *Sardinella longiceps* of the Indian Ocean [Longhurst, 1998].

The abundant Indian oil sardine along the WCI (Figure 1.1) have strong interannual variability and their arrival and departure along the coastal waters coincides with the upwelling bloom [Grinson George et al., 2011]. The putative trophic link of sardine interannual variability is explored as a manifestation of the productivity of the planktonic ecosystem using remote sensing. This is discussed in Chapter 3, in which time series remotely-sensed chlorophyll data representing the food is compared with the biology, migration and landing of sardine.

The entire sardine fishing ground off the southwest coast of India, extending from $5^oN$to 15^oN was considered for the study. The seaward limit of the study area extends upto the outward edge of the continental shelf (200 m isobaths) (Figure 1.1). Figure 1.1 explains the schematic representation of sardine movement, but the actual dwelling area of sardines is segregated in the satellite image by following the depth contour. The spatial extent of the study area was determined in concurrence with earlier observations [Longhurst and Wooster, 1990]. Characteristics of the coastal currents and environmental setting described in the earlier study [Dineshkumar and Srinivas, 2007] also define this study area as a narrow continental shelf domain with strong upwelling and downwelling signatures.

For imbibing specialised features to compare biological abundance and larval transport in different marine ecosystems three unique domains were selected for the study as mentioned earlier:

(a) Gulf of Kachchh: The GoK is located on the northwest coast of India, between $22^o15'N$-$23^o00'N$ and $69^o00'E$-$70^o15'E$ (Figure 1.2) and is approximately 170 km long and 75 km wide at the mouth. Tidal range varies from 3 m at the mouth to 7 m in the upstream and tidal currents reach upto 2 $m.s^{-1}$. The collective contribution of fish production in the GoK during 2007-08 was 18.80% to the total production of Gujarat State. The northern GoK, which is predominantly sandy or muddy and confronted by shoals and creeks, also has large stretches of mangroves. The southern GoK has numerous islands and inlets that has vast areas of mangroves and reefs with living corals. The southern GoK is a productive spawning ground for fishes with mangroves, coral reefs, sea grass, sea weeds and many species of red, green and brown algae. A variety of marine wealth that exists in the

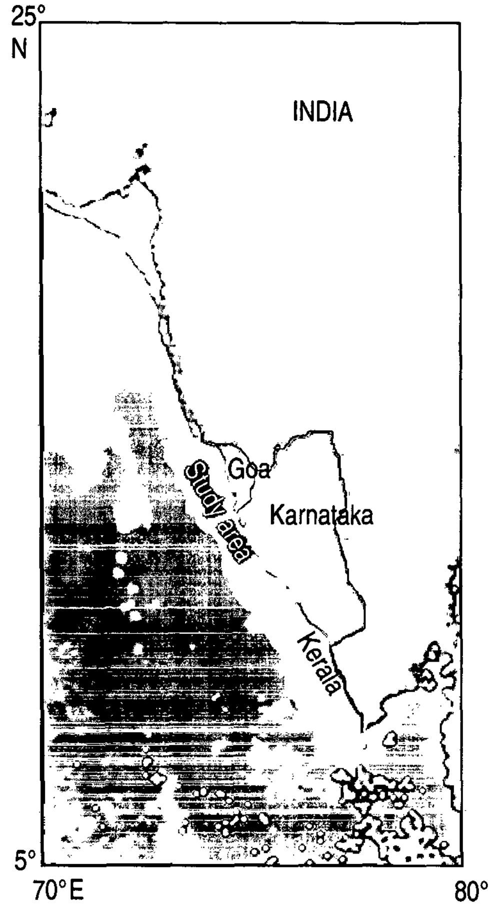


Figure 1.1: Study area of occurence of Indian oil sardine

GoK includes algae, mangroves, corals, sponges, molluscs, prawns, fishes, reptiles, birds and mammals. In order to protect the rich biodiversity of GoK, several long stretches of intertidal mudflats and coral reefs along its southern GoK are Marine National Park and Marine Sanctuary (Figure 1.3). A variety of exposed and sheltered sites are present in the GoK and previous studies show the existence of three distinct eddies with diameters varying between 10 and 20 km in the western half of the GoK [Desa et al., 2002; Vethamony et al., 2004; Babu et al., 2005; Kankara et al., 2007]. The high tidal influx covers vast low lying areas of about 1500 km^2, comprising of creeks, marshy tidal flats and rocky regions which provide congenial

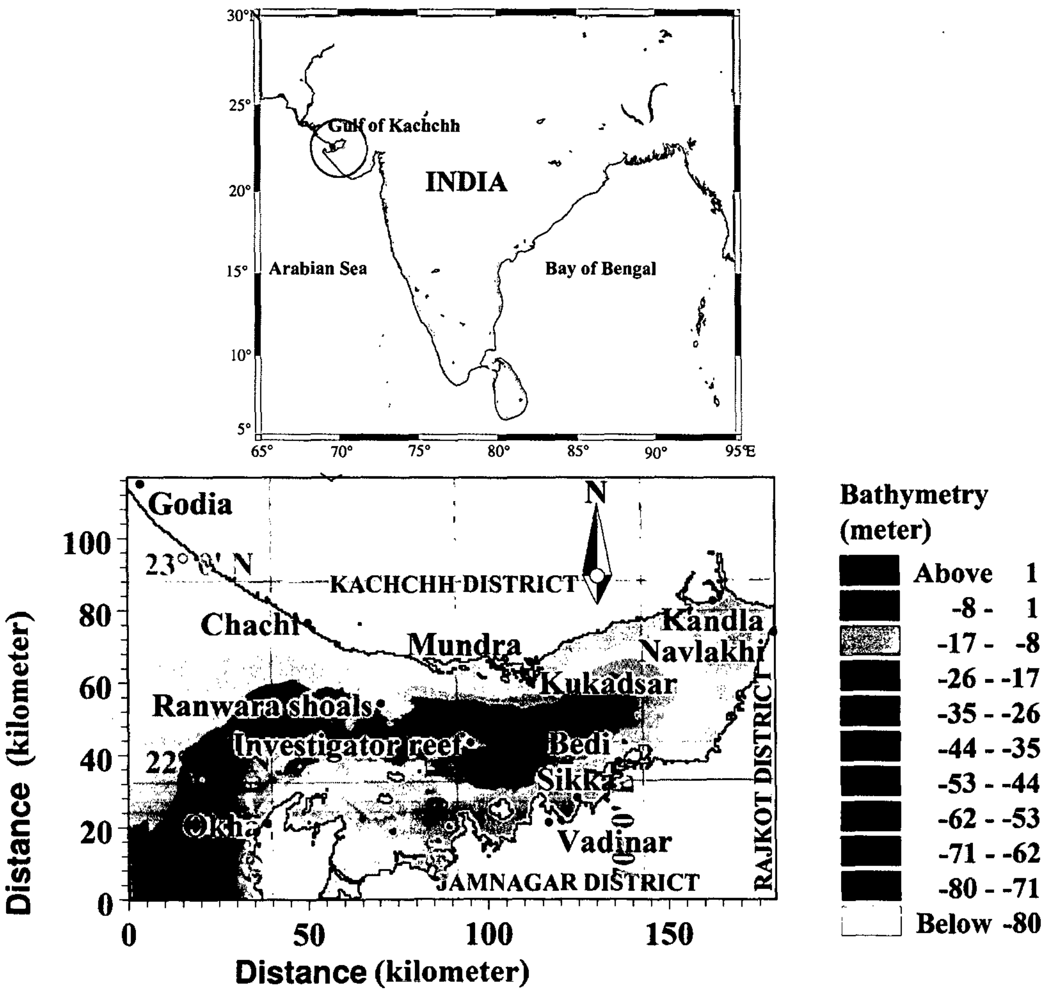


Figure 1.2: GoK and its topographic features with relevant study sites

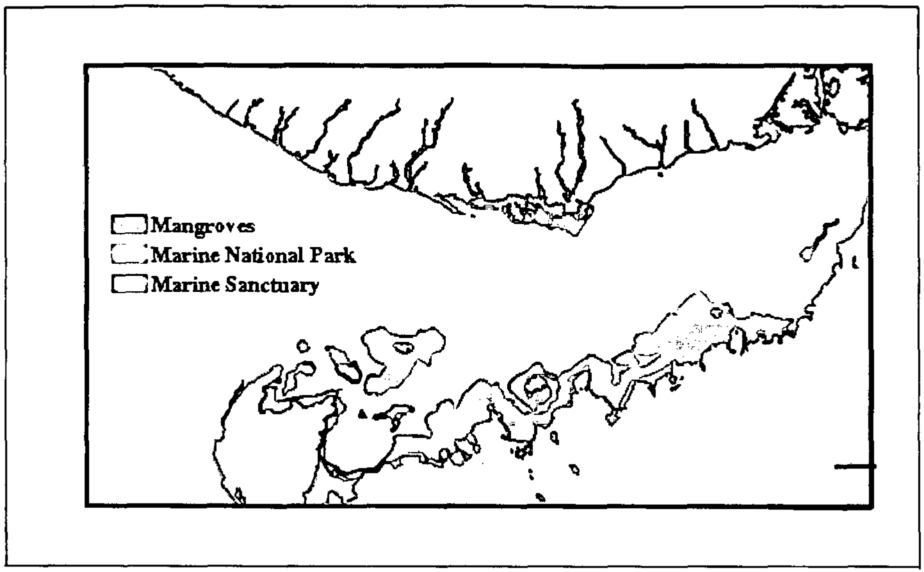


Figure 1.3: Distribution of ecologically sensitive areas along the GoK (reconstructed from Desa et al. [2002]

environment to a wide variety of marine biota.

No study has been carried out so far in the coastal waters of India to determine the influence of physical forcing on fish larvae under which they are widely dispersed or locally retained. We want to assess whether the abundant fish population in the GoK is a manifestation of self recruitment by fishes trapped due to hydrodynamics of the region or geographical barrier. We have released fish eggs as inert conservative particles from their representative spawning sites under a range of hydrodynamic conditions and associated dispersion processes, unique to the GoK to simulate the spreading of eggs and transport of larvae.

(b) Goa coastal region: Goa is located along the central west coast of India, between the latitudes $14^o53'54''N$ and $15^o40'00''N$ and longitudes $73^o40'33''E$ and $74^o20'13''E$. It is flanked by the Arabian Sea with a coastline of 103 km. Mandovi and Zuari, the two major rivers in Goa, form their estuary which is typically a well mixed water body with an average depth of 5 m at the mouth. Throughout the course of these rivers an intricate system of wetlands, tidal marshes and cultivated paddy lands are found which are interconnected by canals, inland water bodies and creeks governed by regular tides. A luxuriant growth of mangroves is found bordering the estuaries thereby, playing a major role in protecting the coast. There are rocky shores and tidal pools in between these sandy stretches which are relevant in the life cycle of many shell fishes. The specific study region (Dona Paula bay, Zuari estuary $15^o 26' 18.44'' N$ and $73^o 47' 53.9'' E$) is shown in Figure 1.4. Rocky shores at Arambol, Anjuna, Singuirim, Dona Paula, Mormugao, Bogmalo, Palolem and Galgibagh are the locations chosen for the model study in the Goa coastal region .

The coastal areas surrounding the Mandovi-Zuari estuarine system are areas of active fishing, practically throughout the year. The quantity of freshwater discharge in Zuari during pre and post monsoon period is negligible (about 0.03 $km^3.year^{-1}$) and therefore, their flow during these seasons is regulated by semi-diurnal tides. Similarly, in Mandovi also, the freshwater discharge during pre and post monsoon period is negligible (about 0.06 $km^3.year^{-1}$). The estuarine system turned out to be an ideal habitat for the barnacle, *Balanus amphitrite*, an important component of the intertidal community, and also of the marine macrofouling community. The cosmopolitan distribution of this organism along the waters off Goa made it an interesting feature to be studied. A coupled two dimensional hydrodynamic and particle tracking model is used to estimate dispersion and retention of barnacle larvae from their possible spawning sites. This is attempted using an Eulerian hydrodynamic model as well as a Lagrangian particle analysis model to simulate the barnacle larval transport. Larvae were released as inert conservative particles from their representative spawning sites under a range of hydrodynamic conditions, unique to the estuary to simulate spreading and weathering of larvae under the influence of prevailing flow and associated processes. An effort is made to validate the modelled larval dispersion using field data. This case-study identifies suitable time and location for larval dispersal and settlement, and accordingly, the maximum and minimum distance the larvae can disperse in different seasons has been calculated.

(c) Mangalore coastal region: This coastal stretch is located along the SW coast of India, between the latitudes $12^o 48' 00'' N$ and $13^o 21' 00'' N$ and longitudes $74^o 36' 00'' E$

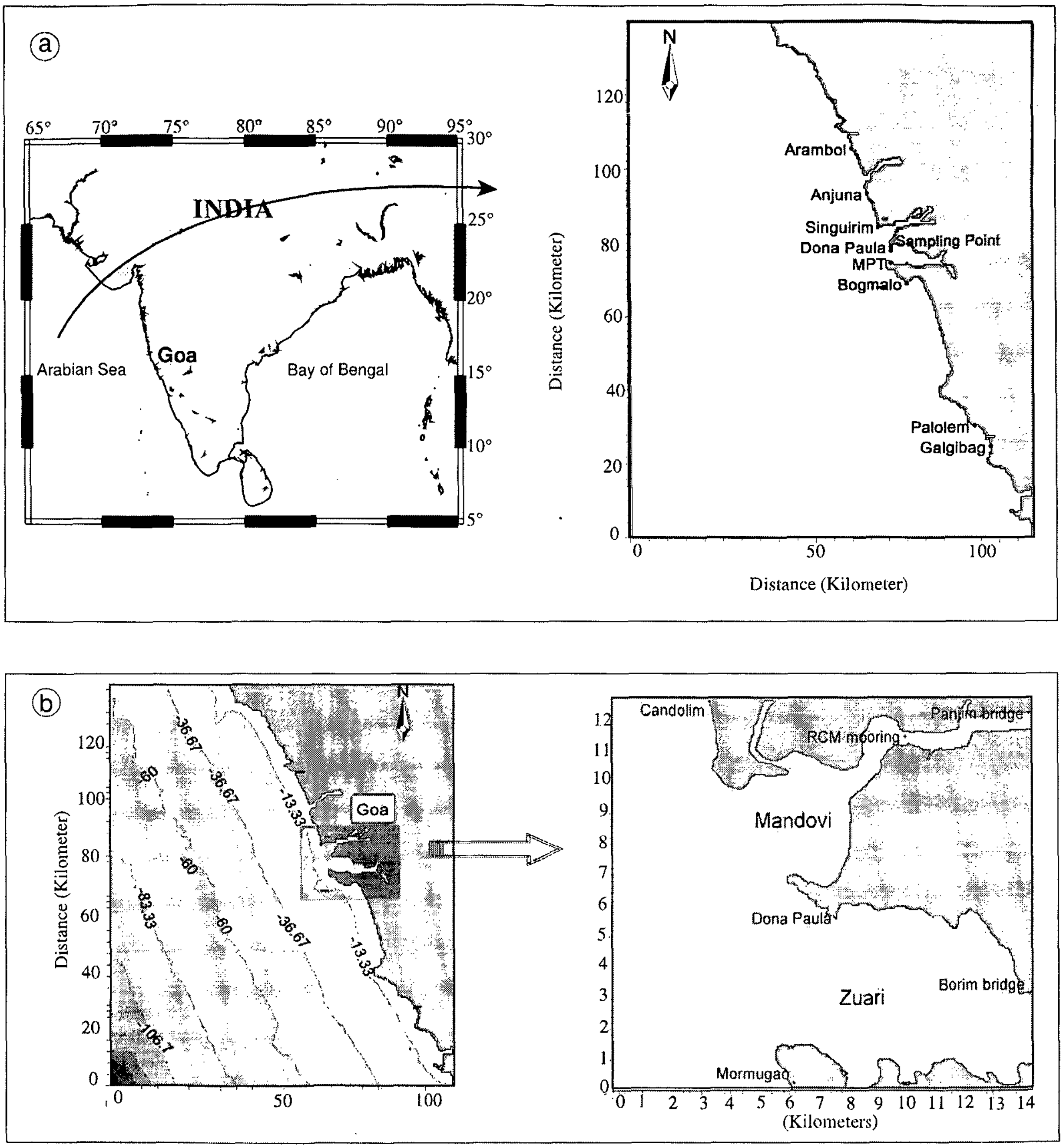


Figure 1.4: Goa study region with (a) large domain and (b) small domain

and $74^o55'00''E$ (Figure 1.5). This dynamic coastal stretch with a well defined Malabar upwelling zone is characterized by diverse fishing and industrial activities. Surveys indicate a clear presence of fishing ground in this region. This region is very dynamic with tidal currents and seasonal wind driven current systems. The river runoff is maximum during the SW monsoon season. The seasonal heavy precipitation is carried into the Arabian Sea through numerous streams and rivers in addition to the land run off. Major river in the study area is Netravati, which contributes to the coastal waters with considerable amount of nutrients and organic matter. These characteristics are likely to influence the fishery potential in the region. The region off Mulki in the coastal waters off Karnataka is an important area with high fishing activity. Therefore, off Mangalore forms an ideal location for studying the larval transport and dispersion of fish larvae.

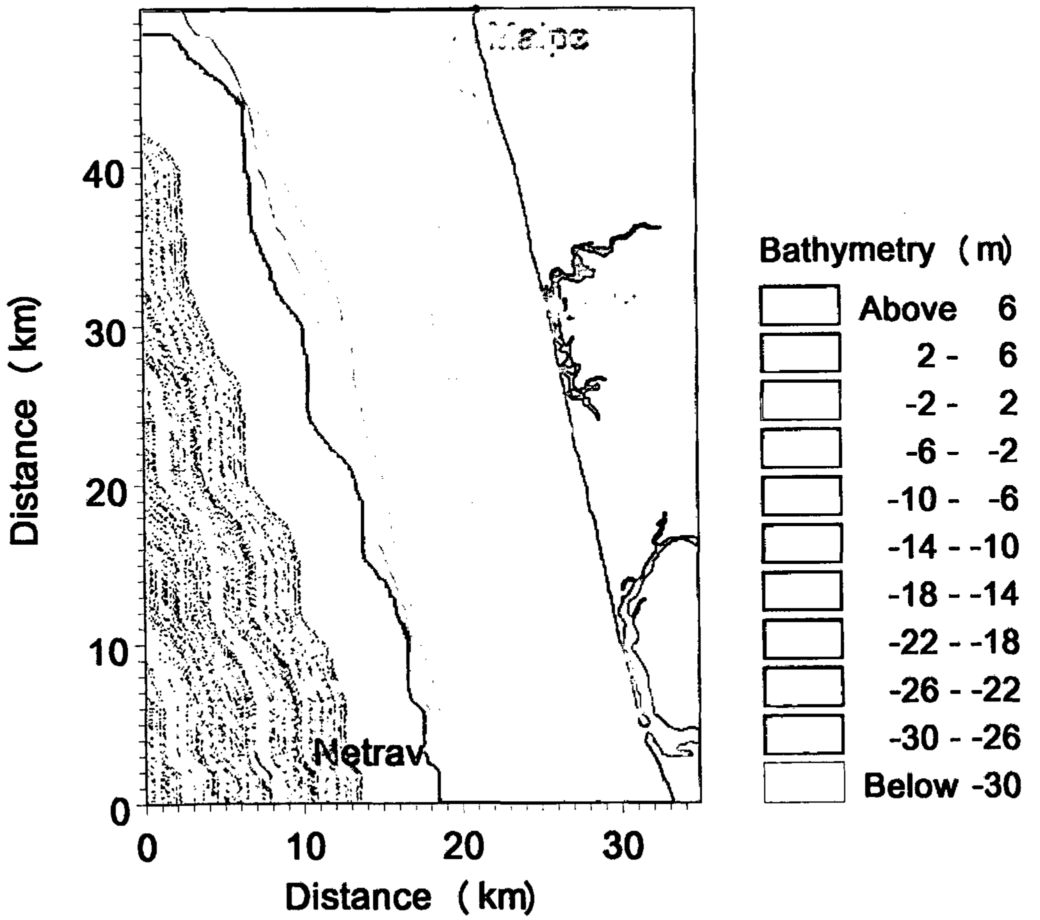


Figure 1.5: Mangalore study region with relevant study sites

Chapter 2

Data and methodology

2.1 Remote sensing data and statistical analysis

Monthly averaged chlorophyll maps at 9 km spatial resolution derived from *Sea-viewing Wide Field of view Sensor (SeaWiFS)* satellite data for the period January 1998 to December 2006 was downloaded from the website of NASA ocean colour (*http://oceancolor.gsfc.-nasa.gov/cgi/l3*) [Oceancolour, 2010]. The optically sensitive constituents such as suspended solids and yellow substance in *Case-2* waters in this region [Menon et al., 2005, 2006] often give undesirable chlorophyll values. This issue was solved during extraction of chlorophyll-a from the composite image using an algorithm for masking turbid waters [Bricaud and Morel, 1987]. A trend between sardine landing and chlorophyll-a has been found using the polynomial trend line, which gave the best fit. Coefficient of determinant was worked out for quantifying the variability in sardine landings and chlorophyll-a during the bloom initiation month.

2.2 Fish landing data

Data on marine fish landings in India for the period 1985-2006 published by the Central Marine Fisheries Research Institute [Srinath et al., 1969] have been used. We collected 316 samples of sardines from the major sardine landing centre at Cochin for length and weight measurements. Sardine catch is dominated by 0-group individuals, *viz.*, measuring $\leq$ 14 cm total length [Pauline and Jakob, 1986], spawned during the earlier spawning period starting from May (Table 2.1). The entire breeding activity of sardines is confined to coastal waters with an active artisanal fishery comprising of motorized and non-motorized crafts with operating gears such as ring, purse and shore seines. This artisanal fishery responds with vital fishing efforts depending on the fish availability. Mechanized trawlers in the coastal waters are restricted to a period of 45 days, starting from 15 June. Decrease in sardine fishery within the study area did not result in heavy landings elsewhere, thus ruling out the possibility of migration of sardines from the study area. Hence, it is assumed that the sardine landings within the study area are representative of stock abundance [Longhurst and Wooster, 1990]. This assumption holds good since the present study is restricted to a time period, when there was relatively little change in the composition of fishing crafts and gears [Grinson George et al., 2011].

Table 2.1 Average length and weight measurements of 316 random sardine samples from a major landing centre

Total Length (cm)	Fork Length (cm)	Std Length (cm)	Gill Girth (cm)	Mouth Diameter (cm)	Weight (gm)
11.64±2.57	10.24±2.28	9.64±2.15	1.77±0.49	0.88±0.39	12.58±10.96

2.3 Field measurements

Measured data on tides, currents, metorological and biological parameters are used for calibration of the model and validation of model results. Tides and currents were measured by Water Level Recorder (WLR) and mooring Recording Current Meters (RCM), respectively. Data on meteorological parameters have been collected by installing Autonomous Weather Station (AWS) at different coastal locations. The field data collected by the National Institute of Oceanography (NIO) for some of the major programmes formed the biological data set. The details of data (primary and secondary) collected for each study area are described below:

2.3.1 Gulf of Kachchh

NIO has been conducting general as well as site-specific studies in the GoK since 1981 as a part of several ongoing developments bordering the Gulf, particularly along the southern coast. The site-specific studies conducted by NIO from time to time have resulted in an extensive database for the concerned segments of the GoK. Various studies on coastal waters of the GoK often reveal significant seasonal changes in its ecology. The study region experiences three distinct seasons: pre monsoon, SW monsoon and NE monsoon. However, field observations are limited during SW monsoon due to rough sea conditions. Data compiled from various segments of the GoK includes off Okha, Salaya, Vadinar, Sikka, Bedi, Navlakhi, Kandla and Mundra (Figure 1.1).

Field measurements carried out in the GoK under the project "Integrated Coastal and Marine Area Management (ICMAM) plan for the Gulf of Kachchh" by NIO [Kankara et al., 2007] and the data in the report "Status of flora and fauna of Gulf of Kachchh" prepared by Vijayalakshmi [2002] are useful in addition to the data received from the NIO Data Centre. The data on the biota of the GoK has been prepared based on secondary data scattered over a wide array of technical reports, scientific reports and published papers. Among the scientific reports from sources other than NIO, the reports from Gujarat Ecological Society are significant as these are bench mark surveys consolidating the available data on geomorphology, marine ecology and threats, socioeconomic profile, agriculture, environmental problems etc. of the GoK [Gupta and Deshmukh, 1999; Gupta et al., 1999]. Issues and problems involved in managing protected areas and a detailed management plan for the Marine National Park and Sanctuary were reported by Singh [1994].

During the ICMAM programme, six sites, A, B, C, D, E and F representing mouth, mid and head of the GoK in the northern and southern boundaries of the GoK were surveyed for fish egg abundance to identify spawning sites (sites marked in Figure 5.3). Egg samples were collected using a 200 $\mu.m$ mesh size net attached with a pre-calibrated TS flow meter to determine the volume of water filtered. After each (surface-horizontal) haul, the samples were fixed in 5% buffered formaldehyde solution. In the laboratory, an aliquot with a volume of minimum 5 ml was analysed for enumeration of groups. When the total quantity of egg sample was more than 5 ml, it was sub-sampled (Folsom plankton splitter) and only a fraction was counted. The samples were transferred to a counting chamber (petridish provided with a grid of 1 cm^2) for numerically counting the eggs.

Three prominent seasons namely, pre monsoon, SW monsoon and NE monsoon are prevalent in the GoK [Babu et al., 2005]. Hence, recording current meter (model: RCM7; make: Aanderaa, Norway) data measured off Okha, mid-central Gulf and off Kukadsar during April 2002 and November 2002, representing pre monsoon and NE monsoon seasons respectively, were used for model validation. The current speed and direction was resolved into u-velocity and v-velocity components representing currents in the east-west direction (east is considered as positive and west is negative) and north-south direction (north is considered as positive and south is negative), respectively.

Secondary data on fisheries of the GoK were collected from the Department of Fisheries, Gujarat. Trawl catch composition data were collected from the NIO Data Centre.

2.3.2 Goa

The simulated water levels and current velocities have been validated with predicted water levels and measured currents off Captain of Ports (COP), Panaji (location is marked in Figure 1.4). Currents were measured for every 10 minutes interval using Recording Current Meter (model: RCM7; make: Aanderaa, Norway) during 14 November to 10 December 2007. The current speed and direction was resolved into u-velocity and v-velocity components. The validated model has been used to simulate flow patterns for the entire model domain for the periods May 2007, October 2007 and December 2006.

The spawning sites for larval release were selected on the basis of an exploratory survey conducted in the study site. The spawning sites were Vengurla, Arambol, Anjuna, Singuirim, Dona Paula, Mormugao Port, Bogmalo and Galgibagh from north to south. The spawning sites were selected based on visual observations on the occurrence of barnacles in the rocky habitat. This rocky intertidal habitat is immersed on hourly basis for a period of 24 hours during 3 different sampling periods (December 2006, May 2007 and October 2007, representing the three different seasons. Samples were collected with the help of Haron-Trantor net of mesh size 100 μm. The net was towed horizontally with the help of a boat for about 10 minutes. The volume of water filtered was calculated using the number of revolutions obtained with a flow meter. The samples were preserved in 5% formaldehyde, and later sorted and counted under dissection microscope to determine their abundance.

2.3.3 Mangalore

The simulated water levels and current velocities have been validated with predicted water levels and measured currents at Suratkal and Mulki. Currents measured for every 10 minutes interval using Recording Current Meter during 14 November to 10 December 2007 are used for model validation. The current measurement location is marked in Figure 1.4. The current speed and direction was resolved into u-velocity and v-velocity components. The validated model has been used to simulate flow patterns for the study area.

Fish egg and larval studies carried out for assessing fishery, fish spawning grounds and icthyoplankton studies in the coastal waters off Mangalore have been compiled [Verlecar et al., 1998] from the NIO Data Centre and used for interpreting the model results in the Mangalore region. In order to understand the distribution pattern of fish eggs and larvae, samples were taken from the coastal waters off Mangalore fishing harbour every month during September 1997 to May 1998 and in October 1998 by:

(i) Vertical hauls by Hansen egg net (mesh size 60 μm

(ii) Horizontal haul

(iii) Oblique haul by Heron Tranter (HT) net (mouth area 0.25 m^2; mesh size 330 μm.

Zooplankton samples were collected by horizontal, oblique and vertical hauls using a HT in the coastal waters off Mangalore. The sampling was done at 3 water depths in the 5 m, 10 m and 15 m depth contours. A calibrated flow meter was attached to the mouth of the net to record the volume of seawater filtered through the net.

For horizontal and oblique hauls, the net was towed for 10 minutes duration. The vertical hauls were made by lowering the net near to the bottom at each station and hauling it up slowly to the surface. All the samples were preserved onboard in 5% formaldehyde. The zooplankton samples were analysed for estimation of spatial and temporal variations in standing stock (biomass), distribution and abundance of different groups and their common species. The biomass was estimated by the displacement volume method and expressed as 100 $ml.m^{-3}$. The sub-samples or aliquots were taken by Folsom Plankton Splitter and examined under the stereoscopic binocular microscope for numerical counts of zooplankton groups and species. Fish eggs and larvae were separately picked up from the Hansen Egg Net and HT net hauls. The population density of zooplankton and fish eggs and larvae is expressed as numbers per 100 m^3 water filtered.

2.4 Modelling hydrodynamics

In general, estuarine and nearshore coastal waters are well mixed under the influence of strong tidal currents. Therefore, two dimensional depth averaged models have been used in the earlier studies (in the above 3 regions) to simulate tides and currents. The model results show good match with the observations [Moller, 1984; Unnikrishnan et al., 1999; Vethamony et al., 2004; Ramanamurthy et al., 2005; Babu et al., 2005; Kankara et al., 2007].

In the present study, for the simulation of flow and water level in the coastal waters of GoK, Goa and Mangalore, a two dimensional hydrodynamic model MIKE 21 HD, developed by the Danish Hydraulic Institute, [DHI, 2010] has been used. MIKE21 HD is a depth averaged (vertically homogeneous), two-dimensional (2-D) model that simulates unsteady 2-D flows in one layer. The distribution of currents and water levels are replicated by taking into account the hydraulic characteristics governed by the bed topography, surface wind effects and boundary conditions.

The flow in x and y direction changes the water level according to vertically integrated equations of continuity and conservation of momentum. The governing equations are fully 2-D in the horizontal plane. The HD module uses implicit finite difference method to solve the equations of continuity and conservation of momentum [Chubarenko and Tchepikova., 2001; Babu et al., 2005; Babu, 2005].

$$\frac{\partial \eta}{\partial t}+\frac{\partial uH}{\partial x}+\frac{\partial vH}{\partial y}=0 \tag{2.1}$$

The two depth-averaged momentum equations can be written as:

$$\frac{\partial uH}{\partial t}+\frac{\partial u^2 H}{\partial x}+\frac{\partial uvH}{\partial y}=fvH-gH\frac{\partial \eta}{\partial x}+H\frac{\partial}{\partial x}(K_x\frac{\partial u}{\partial x})+H\frac{\partial}{\partial y}(K_y\frac{\partial u}{\partial y})+\tau_w x-\tau_b x \tag{2.2}$$

$$\frac{\partial vH}{\partial t}+\frac{\partial uvH}{\partial x}+\frac{\partial v^2 H}{\partial y}=-fuH-gH\frac{\partial \eta}{\partial y}+H\frac{\partial}{\partial x}(K_x\frac{\partial v}{\partial x})+H\frac{\partial}{\partial y}(K_y\frac{\partial v}{\partial y})+\tau_w y-\tau_b y \tag{2.3}$$

where t-time; x, y-Cartesian coordinates; u, v-depth averaged velocity components in the x and y directions, respectively; f-Coriolis parameter; g-acceleration due to gravity; K_x, K_y-diffusion coefficients in the x and y directions; $\tau_w x, \tau_w y$-wind stress in x and y directions; $\tau_b x, \tau_b y$-bottom stress in x and y directions. The basic assumption behind these equations is that the water column is well mixed without any stratification.

The flow model can include bottom shear stress, wind shear stress, barometric pressure gradients, Coriolis force, momentum dispersion, sources and sinks, evaporation, flooding and drying and wave radiation stresses. The initial data essential for the HD model includes the orientation of water body to be modelled, latitude and longitude, bathymetry, wind (speed and direction), wave parameters, time step and duration of modelling. The resultant HD gives water level, current speed and direction that has vital importance in larval transport.

Depth averaged assumption is based on shallow water equations by which two average horizontal velocity components (u-component and v-component) can represent the vertical distribution of horizontal velocities. The model uses Alternating Direction Implicit (ADI) techniques to integrate the equations for mass and momentum conservation in the space-time domain [DHI, 2003]. Water levels and flows are resolved on a square or rectangular grid covering the area of interest. The equations for each individual grid line are resolved by a Double Sweep (DS) algorithm. The main inputs to the model are bathymetry, bed resistance coefficients, wind fields, water level and flux boundary conditions [DHI, 2001].

2.4.1 Model domain, bathymetry and grid size

One of the key parameters which resolve the accuracy of model output is bathymetry data. Bathymetry is imperative in the hydraulic behaviour of water body. Setting up of bathymetry includes selection of the area, grid spacing, location and type of boundaries. In a bathymetry file, the study area is defined by the UTM (Universal Transverse Mercator), its geographical position of origin, width and height. Horizontal coordinates are given in easting and northing projected in UTM Zone 43. The UTM zone is found out by the UTM Zone formula [DHI, 2003] given by

$$UTM = \frac{180 + \lambda}{6} + 1 \tag{2.4}$$

where, λ is the geographical longitude of the origin in degrees.

The bathymetry file has been created by digitising the depth values given in the Naval Hydrographic chart (Naval Hydrographic office, Dehra Dun). After digitisation, the depth values are interpolated for the whole domain.

To simulate the flow pattern in the study area, structured numerical grids have been used. In areas where the flow is very complex due to bathymetry, high resolution grids were used for a better representation of the flow. Model domain for each case study is discussed in detail in chapter 4, while discussing the hydrodynamics of respective study region.

2.4.2 Stability criterion

In the numerical integration of geophysical fluids, it is necessary to follow a constraint in the time step of integration. Courant-Friedrichs-Lewy condition (CFL) is a stability criterion, which is a measure of stability. The courant number is an important dimensionless flow parameter that describes how many grid points the celerity propagates within one time step. Courant number is defined as:

$$C_R = c\frac{\Delta t}{\Delta x} \tag{2.5}$$

where, c is the celerity, Δt is the time step and Δx is the grid spacing, where the celerity c is given by

$$c = \sqrt{gh} \tag{2.6}$$

where, g is the gravity and h is the water depth. The maximum value of Courant number which can be used without stability problems is calculated based on the bathymetry. The Courant number should be kept ≤ 2 in cases like flow simulation of coastal waters where the bathymetry gradient is high. The maximum courant number that can be used is determined by the grid size (Δx) and the time step (Δt). By adjusting the time step, Δt, the Courant number is set within the recommended range. This means that in order to be accurate, the integration must be done with a time step, Δt, small enough such that a fluid particle moves only a fraction of the mesh spacing Δx in each step.

Length of simulation is decided specific to each case-study. It varies from days, weeks, months and years depending upon the data required to be simulated for resolving each study.

2.4.3 Calibration parameters

Model calibration is defined as fine tuning of parameters until the numerical model results and the field measurements are within an acceptable tolerance by modifying the boundary conditions and improving the hydro-meteorological forcing input. In the hydrodynamic model calibration, model parameters are chosen such that the model reproduces currents and water level close to the observations. The two parameters adjusted during calibration are:

(i) Roughness coefficient-used in the bottom friction formulation: Bed roughness is considered as a primary calibration parameter. Bed roughness can be applied as spatial roughness coefficient reflecting the surface characteristics of the sea bottom. Bottom friction is an important parameter in shallow water which can act significantly to retard current flow. The roughness of the sea floor varies with sediment variation. The sea sediment bed is usually mobile and its roughness in turn may impact the flow, which acts as a feedback between the sea floor and overlying flows. The bottom shear is described as:

$$\tau_b = \rho C_d U^2 \tag{2.7}$$

where, C_d is the drag coefficient, ρ is the density seawater and U is the depth averaged velocity. The drag coefficient can be specified in one of the following ways: (a) Manning number(M) and (b) Chezy number(C). Manning and Chezy numbers are inter-convertible using the following equation:

$$C = Mh^{\frac{1}{6}} \tag{2.8}$$

Hence, in the present study, Manning number is used for carrying out simulations. Larger the bed resistance value, smaller will be the resultant bed friction. The model determines hydraulic friction losses based on a derivative of the Mannings equation. Sediment characteristics of the respective domains are provided to the model.

(ii) Eddy viscosity-parameterizes horizontal mixing of momentum: Viscosity refers to the measure of the resistance of a fluid which is being deformed by some stress, and eddy viscosity refers to the internal friction generated as laminar flow becomes non-linear and turbulent. Therefore, we have to account for friction in the ocean so that the dissipation of motion can be accounted. Eddy viscosity or turbulent viscosity is the coefficient relating the average shear stress within a turbulent flow of water. The eddy viscosity depends on the fluid density and distance from the sea bed. The eddy viscosity can be specified in one of the three different ways:

Smagorinsky formulae has been used to calculate the eddy viscosity in the present study. The Smagorinsky formulation calculates the eddy viscosity as a time-varying function of the local velocity gradients multiplied by the Smagorinsky constant [DHI, 2001]. The Smagorinsky factor was used mainly to damp out numerical oscillations and stabilize the model. The model allows choosing velocity-based or flux-based eddy viscosity formulations, and velocity-based constant eddy viscosity has been used in the present task. The eddy viscosity can be calculated by using the relation,

$$E \approx K\frac{\Delta x^2}{\Delta t} \tag{2.9}$$

where, E is eddy viscosity, K is an empirical constant that typically ranges between 0.01 and 0.06 [DHI, 2001], Δx is the grid spacing, and Δt is the computational time step.

2.4.4 Wind data and wind friction factor

The wind field over GoK undergoes seasonal changes coinciding with the change of seasons in the Indian Ocean. Since GoK is a semi-enclosed basin, the horizontal variation in the wind field from mouth to head is assumed to be insignificant. Therefore, mean winds are applied (Table 2.2) in the simulations for different seasons based on a previous study by Babu et al. [2005].

Table 2.2 Seasonal variability of mean wind speed and predominant direction in the GoK based on Babu et al. [2005]

Period	Wind speed ($m.s^{-1}$)	Wind direction (^{o})
Pre monsoon	4.5	WNW(292)
SW monsoon	6.5	SSW(247)
NE monsoon	3.5	NNE(337)

In Goa and Mangalore region, the pre monsoon period represents a transition period from winter to summer characterized with very sluggish winds. But in the NE monsoon period winds are stronger. The AWS winds (direction and speed) are used in the hydrodynamic model as one of the input parameter for studying the seasonal variation of wind effect on the surface currents (Figure 2.1).

Wind data measured at Dona Paula (Goa) coastal station at 43.5 m height, were reduced to 10 m height using power law- a method for extrapolating the wind speeds between two heights [Peterson and Hennessey, 1978]. The reduced wind is represented by the following equation:

$$\frac{U}{U_r} = \left[\frac{Z}{Z_r}\right]^m \tag{2.10}$$

where, U_r and U are the wind speeds at the reference height Z_r(10 m) and the height Z (43.5 m), respectively. The exponent, m depends on the values of surface roughness and stability. As AWS is located in a relatively flat terrain area, m is assumed as 1/7. The reduced wind speed becomes:

$$U_{10} = 0.8106U_{43\cdot5} \tag{2.11}$$

2.4.5 Initial and boundary conditions

For a realistic simulation, coastal ocean models need to be initialised and constrained at lateral boundaries of the domain. The hydrodynamics at the model's open boundaries must be accurately specified initially to get accurate current flow inside the model domain. The open boundaries should allow a consistent specification of physical properties at the interface between the interior and the exterior of the computational domain. In general, disturbances generated inside the domain should be able to travel outward across the open boundaries without spurious reflection that would affect internal water flow conditions. Boundary conditions for the model are defined by water levels along the open boundaries. This is to represent flow entering or leaving the system due to some process that may alter the flow rate inside the system. Since the offshore boundary is set only a few tens

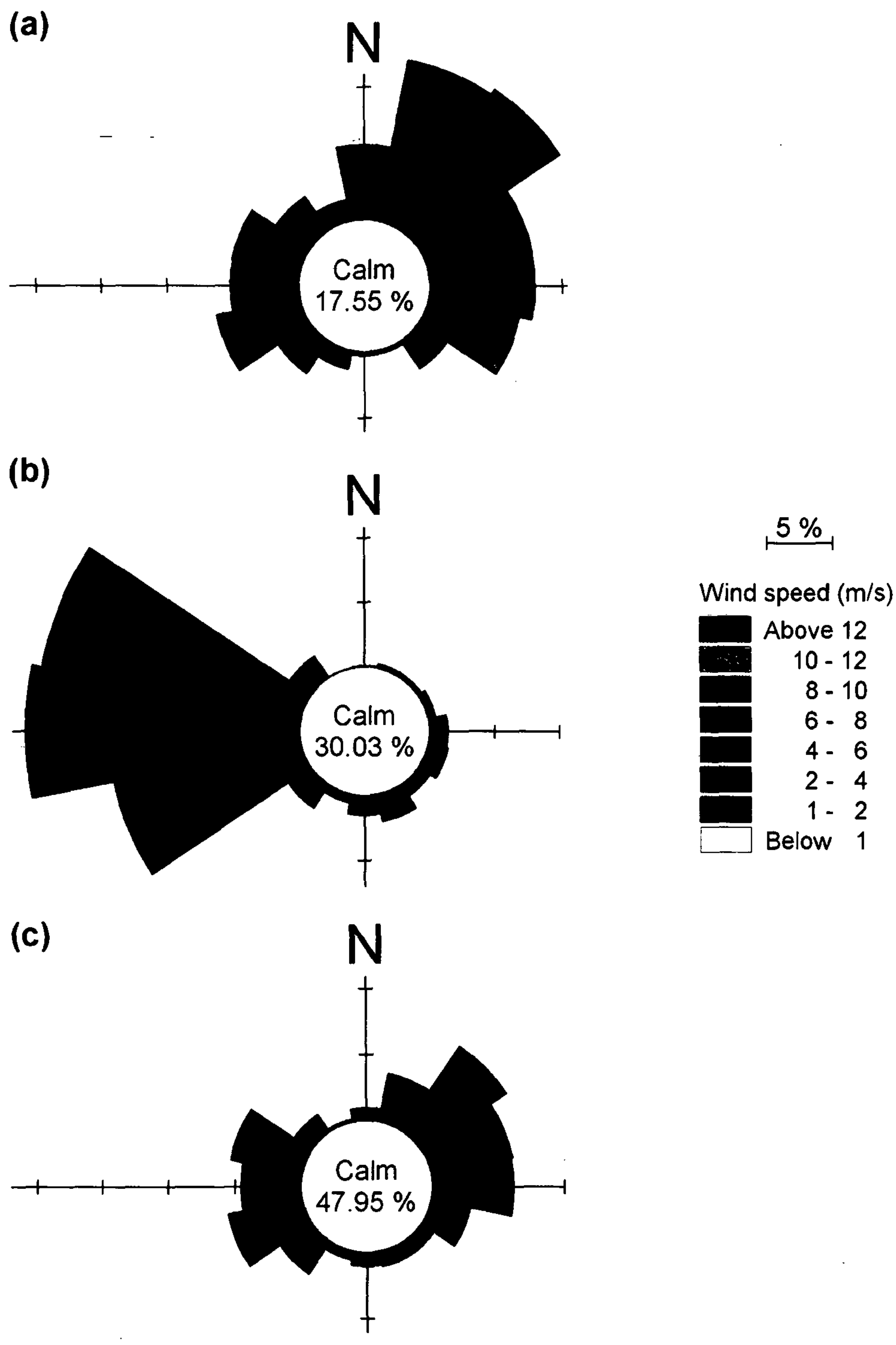


Figure 2.1: Wind rose plot: (a) December 2006 (b) May 2007 and (c) October 2007

of kilometers from the closed land boundary, the water level is assumed to be the same as that of the tidal stations throughout the particular latitude.

The water levels of a particular tidal station at the north and south boundary of the model are specified using MIKE21 tide prediction tool. Tidal constituents from the master tide chart $M2, S2, K1$ and $O1$ (Table 2.3) provided by the International Hydrographic Bureau, Spec. Pub, Monaco (Anonymous 1930) are used for predicting these water levels using Admirality method. The water level along the open boundary in the north-south direction is linearly interpolated. The east boundary is closed by land so that it can be considered as a no flow boundary, except for the small domain simulations of Mandovi-Zuari estuarine systems where tides are predicted for the eastern open boundaries also (Figure 1.4).

A constant water level and zero velocity is used as initial conditions at all grid points. The water level at the open boundaries is used as the boundary condition and the flow direction at the open boundary is considered to be perpendicular to the boundary.

For the GoK domain (Figure 1.2), tide elevations at Okha and Godia creek in the south and northwest boundaries, respectively have been predicted for different periods and the tide elevations between Okha and Godia creek have been spatially interpolated in all grid points along west boundary. East boundary of the GoK between Navlakhi and Kandla is closed as there is no significant fresh water run-off into the GoK [Desa et al., 2002].

For the Goa domain, tide elevations are predicted at Karwar and Vengurla in the south and north boundaries, respectively. The tide elevations between Karwar and Vengurla have been spatially interpolated in all grid points along the west boundary. The east boundary is closed. For the smaller domain (Figure 1.4), tide elevations predicted at Panjim Bridge and Borim using tidal constituents, are used as the boundary conditions in the east boundary. The water levels and fluxes from the large domain simulations are applied as boundary conditions to the smaller domain.

For the Mangalore domain (Figure 1.5), tide elevations are predicted at Mangalore and Malpe in the south and north boundaries, respectively. Tide elevations between Mangalore and Malpe have been spatially interpolated in all the grid points along the west boundary. The east boundary is closed.

Table 2.3 Four major tidal constituents used in the Admirality method of tidal prediction at the boundary stations.

		Tidal constituents							
		M2		S2		K1		o1	
Sl.No.	Location	Amp (m)	Phase (deg)	Amp (m)	Phase (deg)	Amp (m)	Phase (deg)	Amp (m)	Phase (deg)
1	Godia creek	0.864	338.8	0.333	15.6	0.418	63.9	0.211	58.4
2	Dwarka	0.823	325	0.293	359	0.399	54	0.195	53
3	Vengurla	0.553	310	0.193	347	0.313	0.53	0.16	50.8
4	Karwar	0.52	325	0.18	4	0.3	61	0.15	59
5	Malpe	0.43	317	0.15	1	0.3	59	0.13	53
6	Mangalore	0.36	328	0.12	15	0.25	59	0.12	55

2.5 Model parameters evaluation

The quality indices used for comparing model results with measurements are *bias* (mean error), RMS (Root Mean Square Error) and the *correlation coefficient* r. For each measurement, me_{ij} measured at time t_{ij} , the corresponding model value, mo_{ij}, is extracted from the model results using linear interpolation between the model time steps before and after t_i . The quality indices are calculated as follows:

$$dif_i = mo_i - me_i \tag{2.12}$$

$$\overline{me} = \frac{1}{N} \sum_{i=1}^{n} dif_i \tag{2.13}$$

$$RMS = \sqrt{\frac{1}{N} \sum_{i=1}^{n} dif_i^2} \tag{2.14}$$

$$r = \frac{\sum_{i=1}^{n} (me_i - \overline{me})(mo_i - \overline{mo})}{\sqrt{\sum_{i=1}^{n} (me_i - \overline{me})^2 \sum_{i=1}^{n} (mo_i - \overline{mo})^2}} \tag{2.15}$$

Where, me_i is the measured value and mo_i is the model value.

The modelled HD gives water level, current speed and direction that has vital importance in larval transport. The evaluation of these parameters confirms the extent to which the model reproduces the observed hydrodynamic conditions.

2.6 Modelling larval transport

The Particle Analysis (PA) module of the MIKE21 [DHI, 2003] has been used to simulate the larval transport in the study regions. The model simulates transport and fate of dissolved and suspended substances in the aquatic environment under the influence of fluid transport and associated dispersion processes. It uses the Lagrangian random-walk technique to track the movement of the particles released, and the model has been effectively utilized for tracking the retention or dispersion of hypothetical abalone larvae *Haliotis iris* [Stephens et al., 2006].

Fish and barnacle larvae are treated like neutrally buoyant particles with a definite mass. Selecting dispersion coefficients for them is a diffficult process. This is done by calibration of transport processes. The eddy viscosity varies parabolically over the vertical [Deigaard and Hansen, 1994] as given below:

$$v_t(z) = ku_f(1 - \frac{Z}{D}).z \tag{2.16}$$

where k Von karman's constant(0.42), u_f bottom friction velocity, D water depth and z vertical position in the water column.

This model also simulates the spreading and weathering of suspended substance in an aquatic environment under the influence of the fluid transport and the associated dispersion processes. Since the model uses the Lagrangian random-walk technique to track the movement of the particles defined, the same can be effectively utilized for tracking the retention/ dispersion of hypothetical fish and barnacle larvae released within the domain. The model recovers the Lagrangian information from Eulerian velocities obtained through the hydrodynamic model, determining the trajectory of the advected particles from this velocity field throughout time. Larval movement between horizontal grid cells is calculated as

$$V_{l,t} = [R]_{-1}^{1}\sqrt{6D_{l,t}\Delta t} \tag{2.17}$$

where $[R]_{-1}^{1}$ is a random number in the interval -1 to 1, D_l and D_t are the horizontal diffusion coefficients in the longitudinal and transverse directions relative to the current flow, respectively, and Δt is the model time step. The particles that move out of the computational domain through the open boundary are assumed to lose their identity and do not return.

2.7 Larvae- defined based on regional variations and dominating species

2.7.1 Gulf of Kachchh

During 2007-2008, total fish landing for Gujarat was $6.77*10^5 t$, contributing 22.37% to the total Indian production of $30.27*10^5 t$. The major share is from Jamnagar and Kachchh districts. Though there are fluctuations in total fish landings, there has been a steady growth in fish production from 1983-84 onwards, except minor fluctuations in 1995-1996 and 1998-1999 (Figure 2.2).

A total of 27 categories of fish were recorded from the GoK (Figure 2.3) during 1999-2000 with sciaenid (34%) dominating the catch [Vijayalakshmi, 2002]. Since croakers belonging to sciaenidae family formed the major component of fishery in the GoK, sciaenid is considered as the bench mark in deciding the larval transport model parameters. Therefore, in the present study, for the simulation of fish larval transport, the following assumptions are proposed:

(i) period of simulation: based on planktonic larval duration of the sciaenid, which is similar to other tropical fish species too.

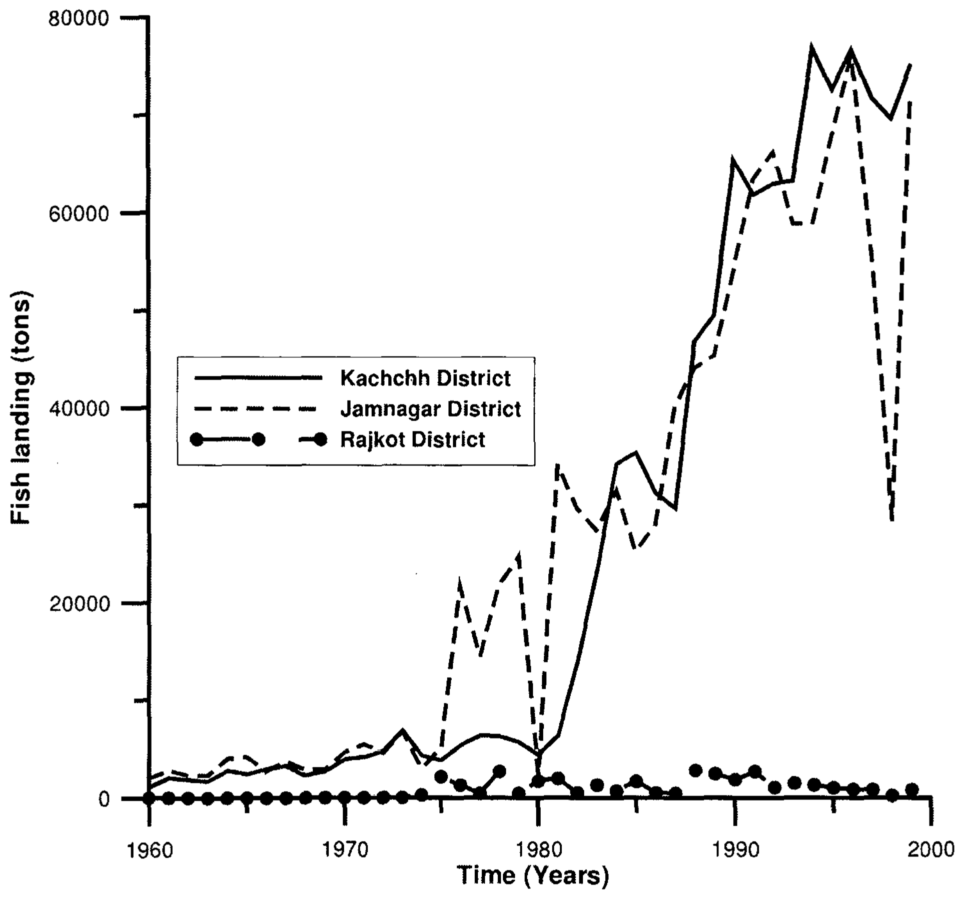


Figure 2.2: Marine fish landing in the three districts of Gulf of Kachchh during 1960-2000

(ii) particle size of released eggs: based on the egg size, weight and fecundity of sciaenids. The estimated time of hatch based on the sampling point time was controlled using a source flux defining the mass and release of larvae at selected spawning sites.

(iii) possibility of passive drifting: based on swimming speed of the sciaenid

(iv) total particles released: eggs were estimated based on the fecundity of the sciaenid. Particle release time is based on the spawning time of sciaenid. One particle released in the model is estimated to be equivalent to 100 eggs as fecundity of tropical fishes tend to vary from 0.1 to 1 million [Pandian, 2003]. Release of 10 million eggs is achieved by assuming that a minimum of 10 fishes are spawning in a site during the active breeding phase with each egg weighing 0.02 mg weight [Gustavo et al., 2003] as estimated for sciaenid in tropical waters (the most dominant group of fish found in the GoK).

(v) virtual fish eggs are simulated as neutrally buoyant passive particles. Released eggs form larvae in a day in tropical conditions as their hatching time is reported to be less than a day [Pauly and Pullin, 1988]. For a smooth illustration of events during larval transport, the tracer particles used in the model are termed as eggs at the spawning site, and larvae thereafter as eggs develop into larvae in a day in sciaenid fishes. Hence, hypothetical larvae were allowed to disperse following the egg release from two major spawning sites identified from the six survey sites for each season.

(vi) active fish larvae tend to migrate vertically. But, a well mixed current regime similar to the GoK tends to carry forward the larvae. The difference in trajectory may result in a shift in their distribution to the order of hundreds of meters, but limitations of a 2-D depth averaged model in a 500 m grid spacing make it difficult to consider this possibility, and it is assumed that the changes in distribution of larvae due to vertical migration is negligible for the study.

To visualize the movement of fish larvae, particle-tracking was simulated for the 6 spawning locations surveyed for egg abundance in the GoK and tracked for 30 days. Final site selection for egg release in the PA model was decided based on the egg abundance and dispersal pattern observed from the particle tracking results.

In this study, we assume that fish larvae are transported with the flow without being settled. The assumption of a purely pelagic phase is supported in some systems, but lab/field observations sometimes contradict the assumption that the larval component is completely passive [Leis, 2006]. In a macro-tidal regime like the GoK, weak swimmers will not contribute to dispersal trajectories because of strong currents. Tropical sciaenid fishes have a swimming speed of 0.6 to 1.4 $cm.s^{-1}$ [Leis et al., 2006b], but the current speed is of the order of 150-200 $cm.s^{-1}$. The larvae complete their Planktonic Larval Duration (PLD) in approximately 20 days, as for most tropical fish larvae [Wellington and Victor, 1989]. The larvae are tracked hourly in this experiment to identify their patterns of dispersal and retention. Dispersed patterns are presented as snap shots in the results at different time steps (day 1, day 5, day 10 and day 16). The larval abundance in a region is affected by predation, mortality and behaviour. In this study, these aspects were neglected as the variation in these parameters in the study domain is not known, and it is difficult to interpolate the same in spatial scales in the numerical model.

2.7.2 Goa

Barnacle larvae are defined as neutrally buoyant, and they follow the prevailing flow without being settled. But its PLD phase is approximated as 10 days for the study after which they are treated as settled. On completion of its PLD phase (610 days), the larvae will settle down if a suitable rocky substratum is available; else it will continue its PLD phase for few more days in search of a viable substratum and finally perishes if it fails to settle in a hard substratum. In the numerical simulations, it is defined that one particle is equivalent to 1000 larvae as it is difficult to model larval transport with huge number of particles. At each time step 4000 number of larvae are released making it into 11.92 million hypothetical larvae over 2980 time steps (with a time step interval of 30 s). The release is so continued for 24 hours and 50 minutes covering 2 tidal cycles as the source

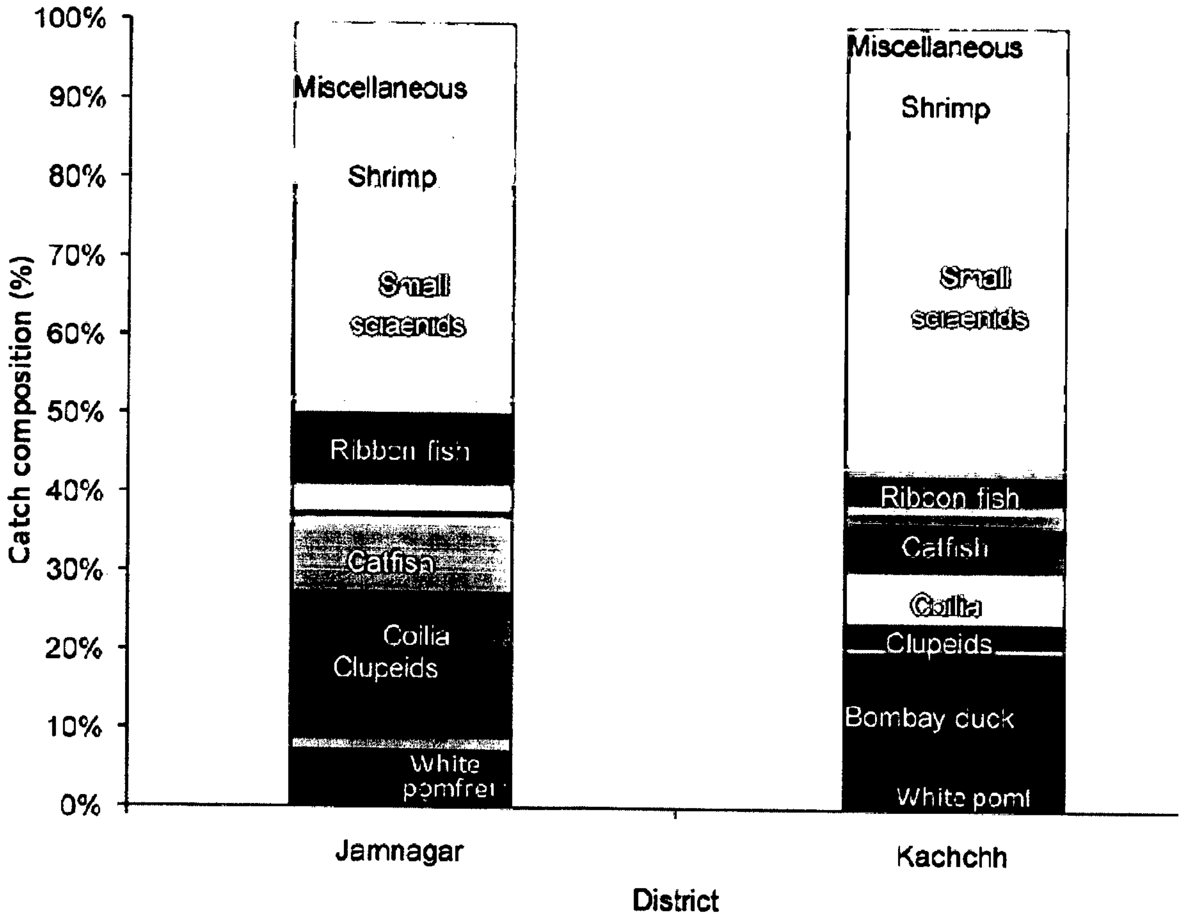


Figure 2.3: Species composition of fish in the GoK

flux. Assuming a mass of 5 μg for each larva, 0.2 mg of larvae per second was released in each time step. The simulations have been carried out for 15 days duration in each season, considering the release of larvae on 6th day and observed the larval transport for next 9 days after the release. Dispersion of the larvae according to the prevailing flow was analysed for each season. The dispersal pattern at the beginning (after complete release of the larva), middle and end of the simulation has been plotted to visualize the larval dispersion.

The concentration, viz., number of hypothetical larvae for each unique hydrodynamic situation is also extracted at various sampling stations to assess the intensity of retention or dispersal under the influence of flow and associated dispersion processes.

2.7.3 Mangalore

One million fish larvae is defined as one particle. Two particles were released simultaneously as pelagic species with high fecundity like sardine dominates the fishery of Mangalore region. The release (source flux) is continued for 24 hours and 50 minutes covering 2 tidal cycles. Larvae were allowed to disperse in the currents following their release. The dispersal or retention pattern of the larvae has been estimated every 30 s. This time step is reasonable to calculate the larval transport in the prevailing flow.

Chapter 3

Tracking the survival of Indian oil sardine larvae using satellite-derived chlorophyll

3.1 Background

The interannual variability in the landings of Indian oil sardines, *Sardinella longiceps* Valenciennes,1847 (hereafter called sardines) has been explained as an outcome of seasonal variability in the marine environment [Hornell, 1910a]. Based on the physical parameters and processes such as sea surface temperature, rainfall, sea level and upwelling, indices relating to total sardine catch with environmental factors are formulated [Longhurst and Wooster, 1990]. These indices formulated based on a correlation between sardine catch and rainfall, wind stress and sealevel failed with time as a result of large variability in landings and correlated factors [Madhupratap et al., 1994]. However, these indices should not be dismissed summarily on the assumption that data were faulty, the criteria for comparison were ill founded, or the relation was spurious; rather, the cause and effect should be explored in detail to explain the phenomena [Skud, 1983]. There are several interrelated factors that are responsible for the recruitment of fishes and their abundance and estimation of these environmental factors is a difficult task. Therefore, biomass based production models such as surplus production models, growth-recruitment models and time series models are used generally, but have have their own inherant limitations. Subsequently, models incorporating changes in physical factors affecting marine food-web gained significance. The concept of fish stock assessment rather concentrates now on predicting the expectant biomass based on ambient environment changes that have a trophic link [ICES, 2000]. Thus, the focus of this present study is to find out the influence of environmental parameters (for *e.g.* chlorophyll-a, as an indirect index of food availability) on the biology of Indian oil sardine [Grinson George et al., 2011].

3.1.1 Biology of sardine

Biological studies suggest an extended spawning period from May to September for sardines [Hornell, 1910a; Hornell and Nayadu, 1924a; Raja, 1969; Prabhu and Dhulked, 1970]. After occlusion from the egg, larval development is rapid in sardines with yolk sac absorption taking place in 3 days [Nair, 1960]. These larvae will undergo their critical first feeding period almost immediately after yolk absorption [Lasker, 1975; Hunter, 2010; Lasker, 1960]. The earliest spawned surviving individuals will be recruited to the fishery by the end of the spawning period, which in turn determines the yearly landings. Thus, larval ecology decides the later abundance of recruits to the fishery. Collating various information cited on young, juvenile and adult sardines and their feed during spawning period [Hornell, 1910a; Hornell and Nayadu, 1924a; John and Menon, 1942; Devanesan, 1943a; der Lingen, 2002], we can confirm that the larvae are predominantly surface and column feeders, with phytoplankton forming a major group, dominated by diatoms like *Fragillaria oceanica*, *Pleurosigma* sp. and *Coscinodiscus* sp. [Nair, 1959; Kuthalingam, 1960].

Sardines feature a fine-meshed filtering apparatus in their gillrakers with more than 130 gillrakers on the lower part of the gill arch [der Lingen, 2002]. They are able to filter smaller particles. Therefore, they thrive on very tiny particles that may predominate throughout their range of distribution in the coastal waters through which they continually migrate [Bakun and Broad, 2003]. Moreover, sardines are serial batch spawners (as are anchovies, sprats, tunas, *etc*). They spawn for several times during their protracted spawning season. The fact that sardines employ a combination of spawning, feeding and migratory habits, underlines the importance of studying sardines during the spawning season along with their feed availability in their course of migration.

The Hjort-Cushing hypothesis [Hjort, 1914; Cushing, 1974, 1990] refers to the critical first feeding period and the timing of the spring phytoplankton bloom. In the case of sardine larvae, upwelling-induced bloom decides its biology. Bloom initiation time and bloom intensity are the factors that could account for changes in the food supply of sardine larvae. These variations in food supply between different years will be reflected in the larval development and further recruitment of sardines into the fishery. This aspect was not examined in the earlier studies on sardine landing variability.

3.1.2 Migratory pattern exhibited by Indian oil sardine

Sardines perform a normal migration from offshore to coastal waters and *vice-versa* coinciding with the customary wind conditions [Hornell, 1910b]. A gradual increase in temperature within the range of 26 to 28^0C is favourable for the inshore migration of the juveniles, and during March to May they disappear to deeper waters due to increasing temperature (above 29^0C) [Chidambaram, 1950]. The specific gravity of water (above 1.023) also promotes the disappearance of the shoals during the above period. The shoreward migration of spawners during SW monsoon season and their outward migration to deeper waters during postmonsoon months is for feeding [Nair, 1959] on phytoplankton that blooms up during the onset of monsoon and continues till post monsoon [Hornell and Nayadu, 1924b; Hornell, 1910b; Chidambaram, 1950; Nair, 1953]. The longitudinal migration either way is an excursion from offshore to inshore waters and *vice-versa* due to availability of food and favourable hydrographic conditions [Devanesan, 1943b]. The shoals start disappearing from the northern region first, and then from the southern Malabar area. From April to September, the shoals of spawners and juveniles migrate from offshore to inshore all along the west coast following the onset of bloom [Raja, 1943]. This observation suggests a northward migration of sardines steadily during SW monsoon season and retrogression from north to south in the NE monsoon season [Hornell, 1910a; Chidambaram, 1950; Panikkar, 1952] (Figure 3.1). Lack of continuous seasonal information to characterize synoptic scale variability in chlorophyll concentration of the region was an impediment to verifying the food availability between different years and to explain the interannual variability in sardine landings. Also, it was not feasible to study the spatial and temporal variations in chlorophyll concentration in these areas because of nonavailability of *in situ* data. With the advent of remote sensing, however, this was possible with ocean-colour data. Platt et al. [2003] applied remotely sensed ocean-colour data as direct evidence for a putative trophic link, and suggested it as an important link in future analysis of dwindling fish stocks. Time series of phytoplankton cycle derived

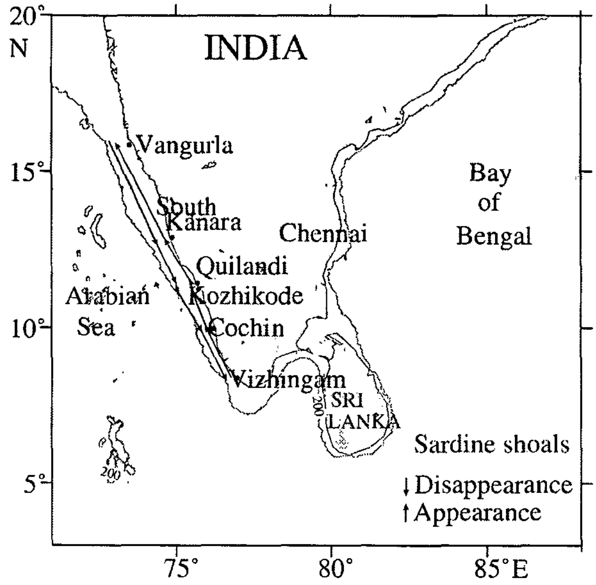


Figure 3.1: Schematic representation of progression of sardine shoals from Vizhingam to Vangurla [Hornell, 1910a; Chidambaram, 1950] and their departure in the reverse direction [Panikkar, 1952]

from satellite data can be used to construct a variety of ecological indicators of the pelagic system useful in ecosystem-based management [Platt et al., 2009].

3.1.3 Relevance of satellite data in explaining the biology and migration of Indian oil sardines

Remotely sensed sea surface temperature (SST) and ocean-colour images reveal eddies and fronts. These features frequently coincide with areas where fish species aggregate as a result of enhanced primary productivity and phytoplankton biomass, which in turn is linked with increased nutrient supply. Since, higher plant biomass is associated with zooplankton abundance, this could provide supplementary information on fish stock distribution from ocean-colour pigment fields. Ocean colour patterns were useful in differentiating the relevance of food over other environmental factors like temperature in fish aggregation, offering better information regarding the location of Albacore tuna [Laurs et al., 1984]. It was originally assumed that tuna prefers to reside within certain limited temperature ranges, which explains their tendency to aggregate at temperature fronts. In instances where colour and SST fronts were spatially separated, they found that tuna actually tend to aggregate on the clear side of a colour front.

Ocean-colour pigments are relevant in detecting a bloom. Fragmented observations in the waters of the southwest coast of India hypothesized two seasonal blooms:

(i) upwelling blooms in May-June coinciding with the arrival of pre-spawning adults and

(ii) winter blooms in September-October coinciding with the main fishery for juveniles [Bensam, 1964].

For sardines, a planktivorous species, the amount of food ingested depends on chlorophyll concentration as well as copepods present in the ambient waters; better availability of food is expected in chlorophyll-rich waters. In the present study, variability in chlorophyll along the waters of the southwest coast of India had been quantified from satellite data and related to annual variability in the sardine landings. The synoptic scale spatial and temporal changes in chlorophyll-a are useful in explaining the appearance and disappearance of sardine shoals along the coastal waters.

3.2 Sardine variability and chlorophyll

The variability in sardine landings, chlorophyll and upwelling bloom initiation were examined for explaining the interannual sardine variability and sardine migration in the coastal waters.

3.2.1 Sardine landing variability

Sardine landing data reveal interannual variability with an increasing trend during the study period (1998-2006). Sardine landings showed a drastic decline in 1985 and 1994

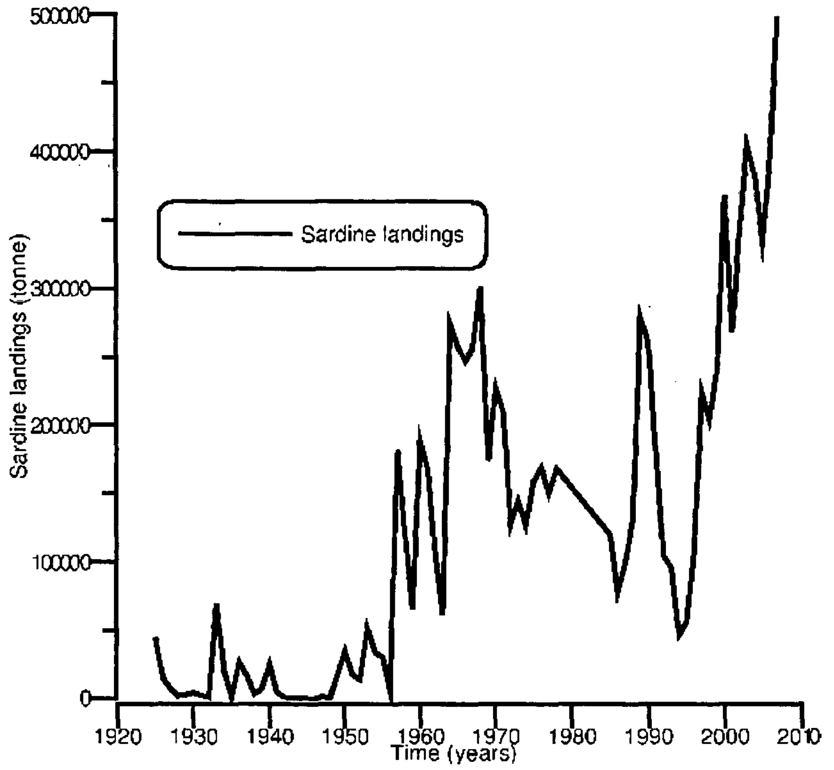


Figure 3.2: Inter annual variability in sardine landing (1925-2006)

(Figure 3.2). Marine fisheries of the southwest coastal waters of India are characterized by predominance of pelagic fish resources (sardines and Indian mackerel *Rastrelliger kanagurta*), which support the largest coastal pelagic fishery along the west coast of India. Alternating patterns of abundance between sardines and mackerel could have been the reason for two major falls in sardine annual landing in 1985 and 1994. The landing pattern of these two species (Figure 3.3) could be compared with the alternating patterns of abundance between sardines and anchovies observed in other upwelling areas of the world. The period 1998-2006 was a sardine dominant period (period of high sardine and low mackerel). Figure 3.3 shows a sardine revival phase, and the period reflects an ideal phase for the study of sardines without interference from the mackerel fishery.

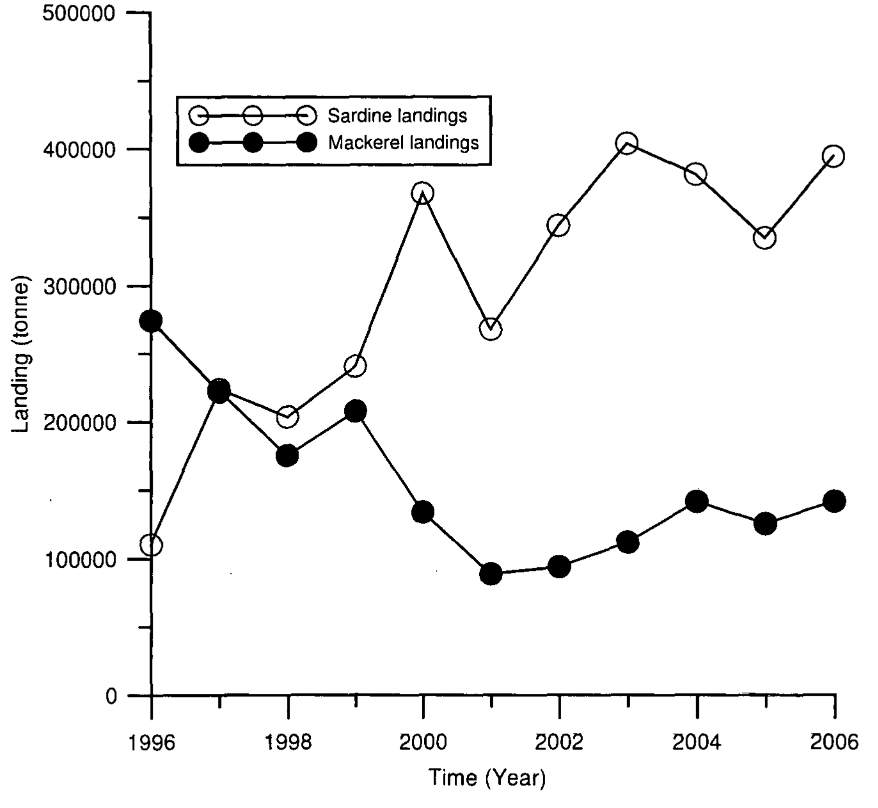


Figure 3.3: Comparison between sardine and mackerel landings (1985-2006)

3.2.2 Chlorophyll variability in the study area

Observed chlorophyll in the study area (Figure 1.1) during 1984-2006 ranged from 0 to 6.25 $mg.m^{-3}$ with a mean value of 0.32 $mg.m^{-3}$ and a standard deviation of 0.59 $mg.m^{-3}$, indicating that chlorophyll available in the coastal waters is highly variable. *SeaWiFS* chlorophyll values remain within the maximum-minimum limits of *in situ* chlorophyll (Figure 3.4) except for the month of August 2002 (6.557 $mg.m^{-3}$), which may be due to an unusually high upwelling bloom.

The chlorophyll-a concentration remained high from May to September, but the peaks varied from year to year. Periods of higher chlorophyll-a concentration match with the active breeding period of sardines (Figure 3.5). The biological calendar of sardines (Figure 3.5) commences with the entry of spawners in May, followed by fresh juveniles during July to August. During September to December, the adults occur in reduced numbers, and the adult population is replaced by large shoals of juveniles. They, however, get numerically reduced in January and February, and subsequently disappear and reappear during May to July. With the onset of pre monsoon showers or SW monsoon rains, they move toward the inshore waters with the gonads in various stages of ripening. The spent and resting adults, on the other hand, appear in small quantities along with their juveniles during January and February, and disappear in the following months along with the juveniles and re-enter for their second spawning along with the virgin spawners. For numerically representing the average chlorophyll, which determines the active breeding phase, chlorophyll concentrations $\geq$1 $mg.m^{-3}$ can be a threshold mark as calculated for the entire study period (Table 3.1). The average monthly chlorophyll-a values in May reached a threshold level of $\geq$1 $mg.m^{-3}$ (Table 3.1). We have examined the suggestion by Madhupratap et al. [1994] that a mismatch *viz.* an early spawning and a time lag in development of food (through a break in monsoon or upwelling) would be detrimental to recruitment.

3.2.3 Sardine landings *vis-a-vis* chlorophyll during bloom initiation

We tested the null hypothesis that the variability in sardine landings was independent of fluctuations in average chlorophyll during bloom initiation month. We could confirm that

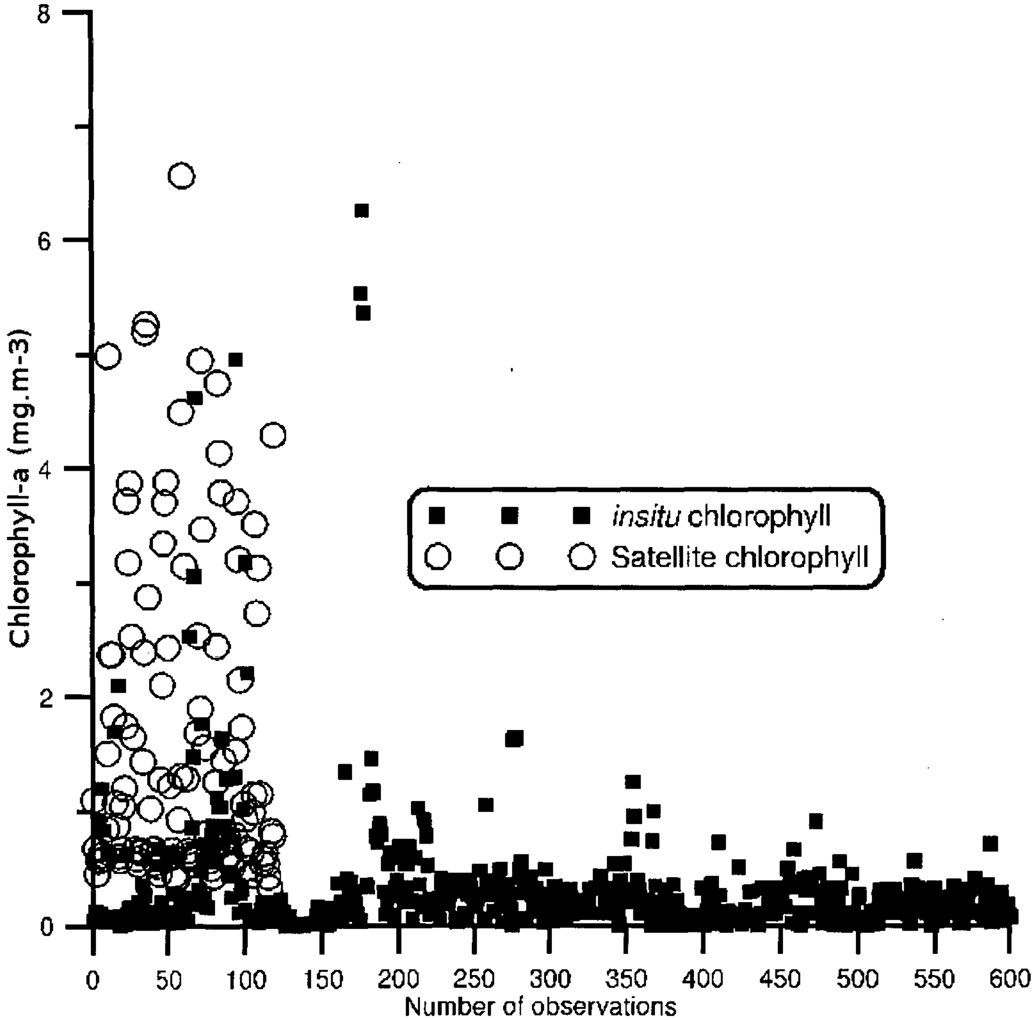
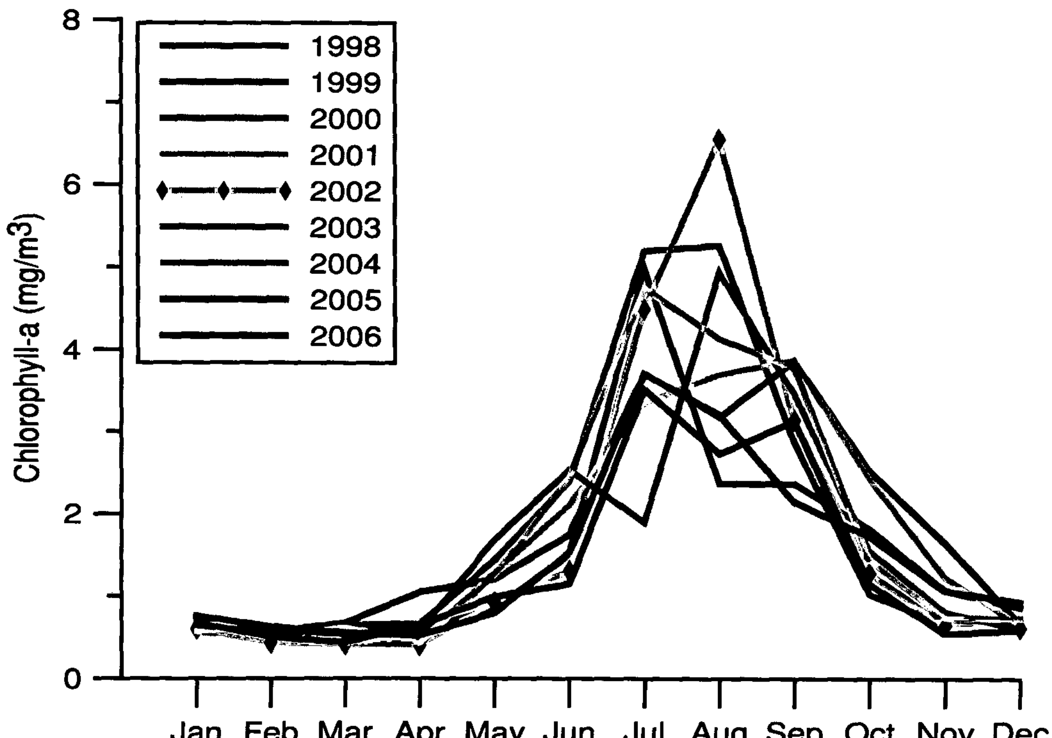


Figure 3.4: Comparison between observed and satellite derived chlorophyll-a during 1984-2006 (data source: NIO Data Centre)



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Biological Calender of Sardine	Immature spent rest	Immature spent rest	Immature spent rest	Immature spent rest	Dev.virgin, maturing	maturing	maturing, mature, Running, Part spent	maturing, mature, Running, Part spent, spent	mature, Running, Part spent, spent	Immature, Running, spent	Immature spent rest, spent	Immature spent rest

(black)	Active Breeding
(white)	Passive Resting

Figure 3.5: Monthly satellite chlorophyll concentration for the period 1998-2006 in relation to biological calendar of sardine. Grey coloured columns in the table show the active breeding phase and remaining columns show the passive resting phase in sardine.

Table 3.1 Monthly averaged chlorophyll during 1998-2006 and corresponding life stage of sardine

Month	Average chlorophyll ($mg.m^{-3}$) during 1998-2006	Life stage of sardine
January	0.618333	immature, spent resting
February	0.540444	immature, spent resting
March	0.546444	immature, spent resting
April	0.593778	immature, spent resting
May	1.158222	maturing, developing virgins
June	1.858333	maturing
July	3.957667	maturing, mature, running, partially spent
August	4.011889	maturing, mature, running, partially spent
September	3.187778	mature, running, partially spent, spent
October	1.666556	Immature, running, spent
November	0.937333	immature, spent resting, spent
December	0.708000	immature, spent resting

39% variability in sardine landings was related to average chlorophyll-a concentration during the bloom initiation month. Figure 3.6 clearly depicts an increase in chlorophyll-a, which is associated with high landings (match), and a decrease in chlorophyll-a, associated with reduced landings (mismatch), except for the year 2002. Apart from chlorophyll, there could be other factors affecting the sardine biomass. But, availability of chlorophyll-rich water in the bloom initiation month will help in better survival of sardine larvae. Early food availability by an upwelling bloom indicated as higher chlorophyll-a in Figure 3.6 is reflected in increased sardine landings, since many of the total larvae recruited were able to survive because of surplus food. Even though *SeaWiFS* data are short, the data do indicate a definite link between chlorophyll-a and sardine landings. Early initiation of phytoplankton bloom may not be sufficient to ensure a higher survival of sardine larvae in the same year, but it is definitely a necessary condition as envisaged in this study. This is well reflected in the sardine landings, since the fishery was dominated by 0-year class fishes (Table 2.1). An unprecedented blooming was observed in 2002 when chlorophyll-a values were the highest during the study period. Thus, the year 2002 was exceptional to have a low chlorophyll in May followed by an unanticipated high chlorophyll period

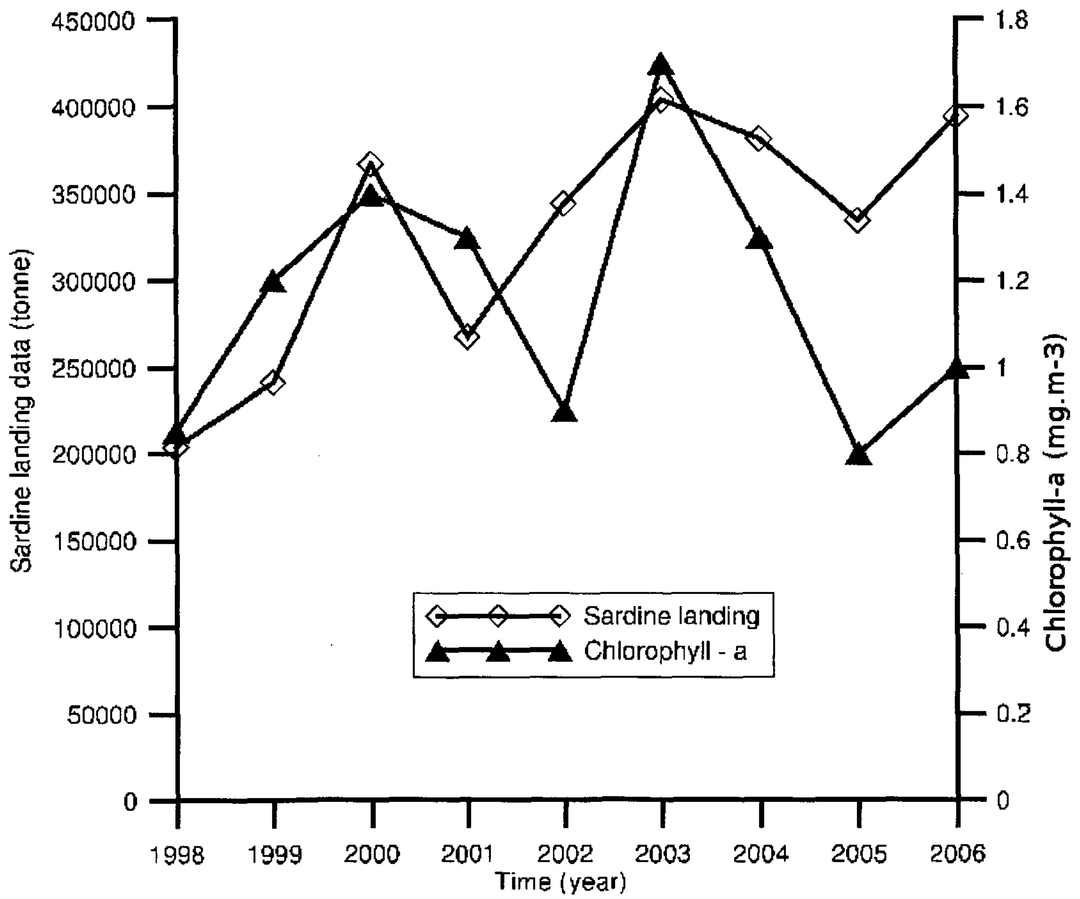


Figure 3.6: Comparison between chlorophyll-a concentration during bloom initiation month and sardine landing

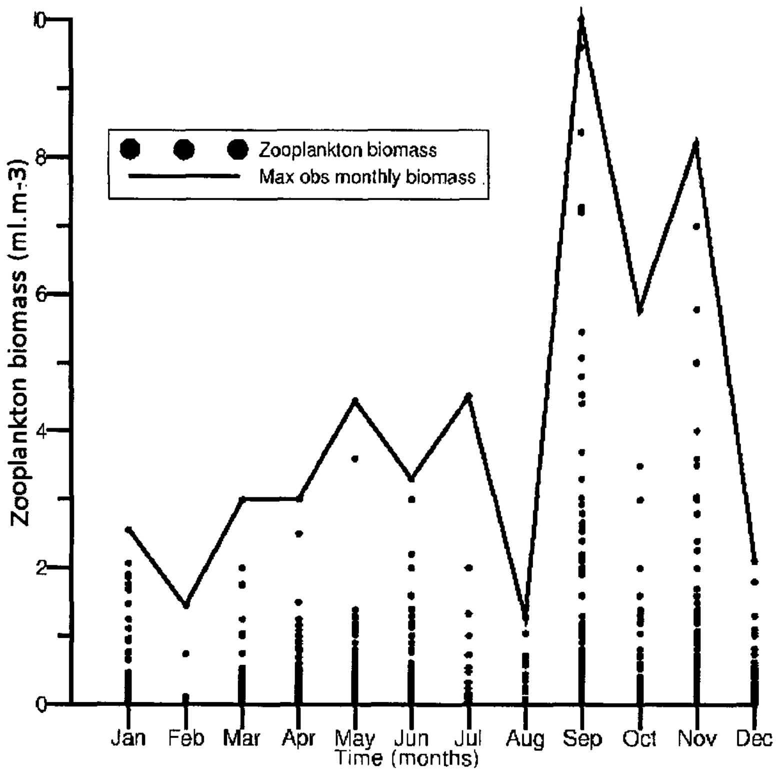


Figure 3.7: Monthly observed zooplankton biomass during 1984-1996 (data source: NIO Data Centre).

(Figure 3.6). Since the spawning period of sardines is protracted, higher survival of the later spawned larvae also could make up for poor survival of early spawned larvae. Gut analysis of sardines shows that, being filter feeders sardines ingest the particulate phytoplankton and zooplankton available in the ambient waters. The phytoplankton bloom (mostly diatoms and dinoflagellites) results in better productivity enhancing the microzooplankton and zooplankton in the Arabian Sea [Madhupratap et al., 2001]. This is true because zooplankton biomass observations in the study area also show several peak values during the months from September to December (Figure 3.7), following the increase in chlorophyll-a.

3.2.4 Seasonal appearance of sardines and chlorophyll

The present study clearly reveals the synoptic scale temporal changes (1998-2006) with respect to chlorophyll availability in the three prominent sardine landing maritime states (Figure 3.8) of India- Kerala, Karnataka and Goa. Figure 3.8 illustrates how chlorophyll-rich waters appear earlier in the south (off Kerala) and move gradually northward, and the pattern reverses during the retrieval of monsoon. The changing intensities of chlorophyll in the coastal waters (area under the graph for each year (Figure 3.8)) of the states describe the possible appearance and disappearance of sardine shoals during the active breeding phase. The quarterly sardine landing in each maritime state (Figure 3.9) follows a proportional change in the chlorophyll concentration. This shows an aggregation response of larval sardines to chlorophyll concentrations.

3.3 Discussion

There was very little change in the fishing effort during 1998-2006, with 238,772 fishing crafts in 2005 [CMFRI, 2005] in comparison to 239,000 crafts in 1997 [Sathiadhas, 2006]. Thus, the increase in sardine landings during the study period, despite steady fishing effort, indicates a link between the food available for sardine in the study area and its intensity, as a reason for the revival of the fishery. Sardines feed predominantly using the fine branchial apparatus on phytoplankton and zooplankton in ambient waters. Chlorophyll-a in a given area, as an index of phytoplankton biomass, is capable of assessing the food availability for sardines.

Summer surface chlorophyll-a concentration estimates from the study area are reported to be 0.1 to 5 $mg.m^{-3}$ for a normal distribution and can be very high, from 5 to 10 $mg.m^{-3}$, during bloom period [Raghavan et al., 2006]. Heavy blooms of *Fragillaria oceanica* were observed in 1949 and 1953 when sardine stock was rebuilt after the population crash of 1940s [Nair, 1953]. This strengthens the view that an early bloom is advantageous for increased larval survival which, otherwise could have perished due to lack of food.

The life cycle of sardines depicts a clear picture of an active breeding season from May

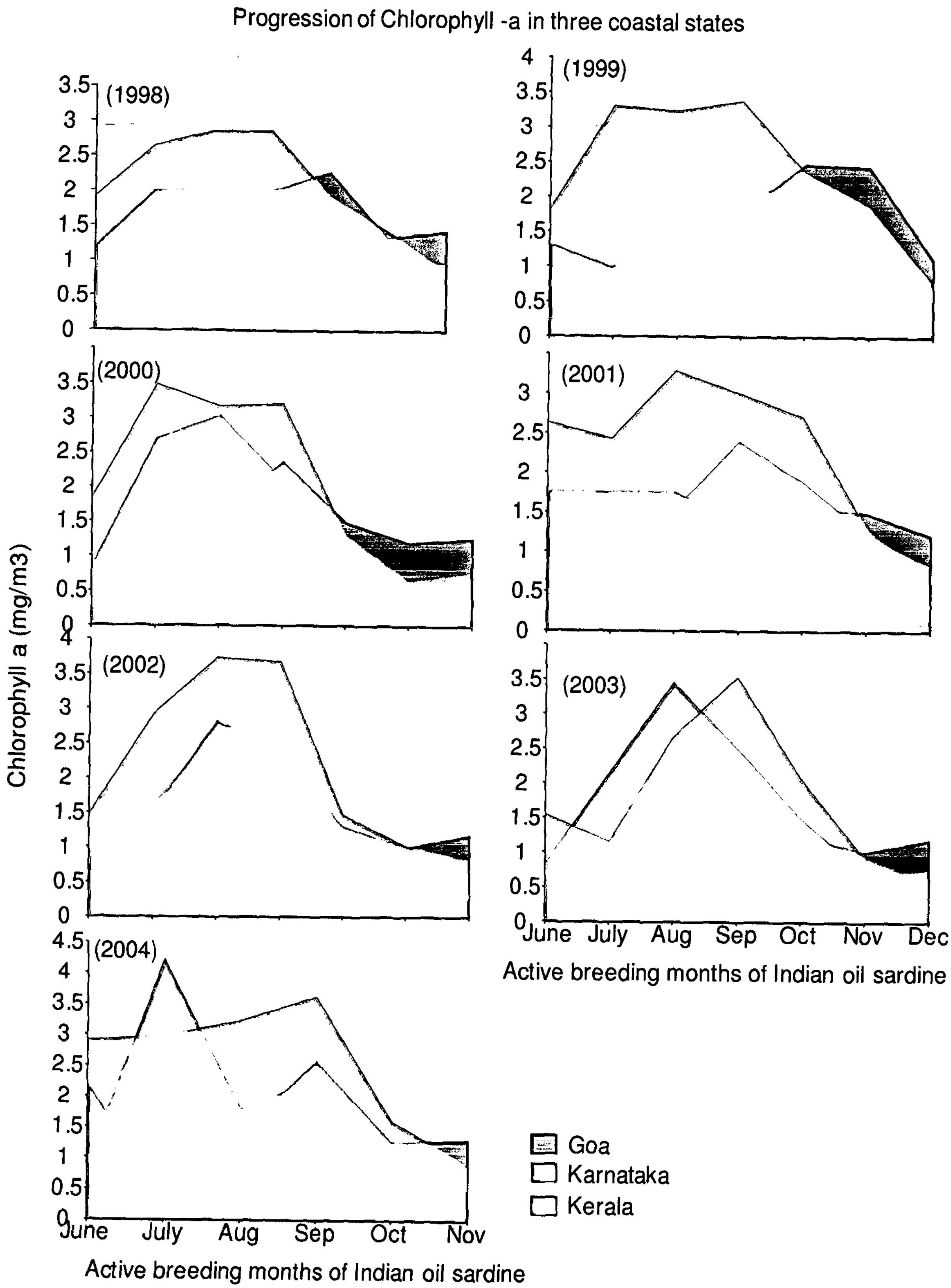
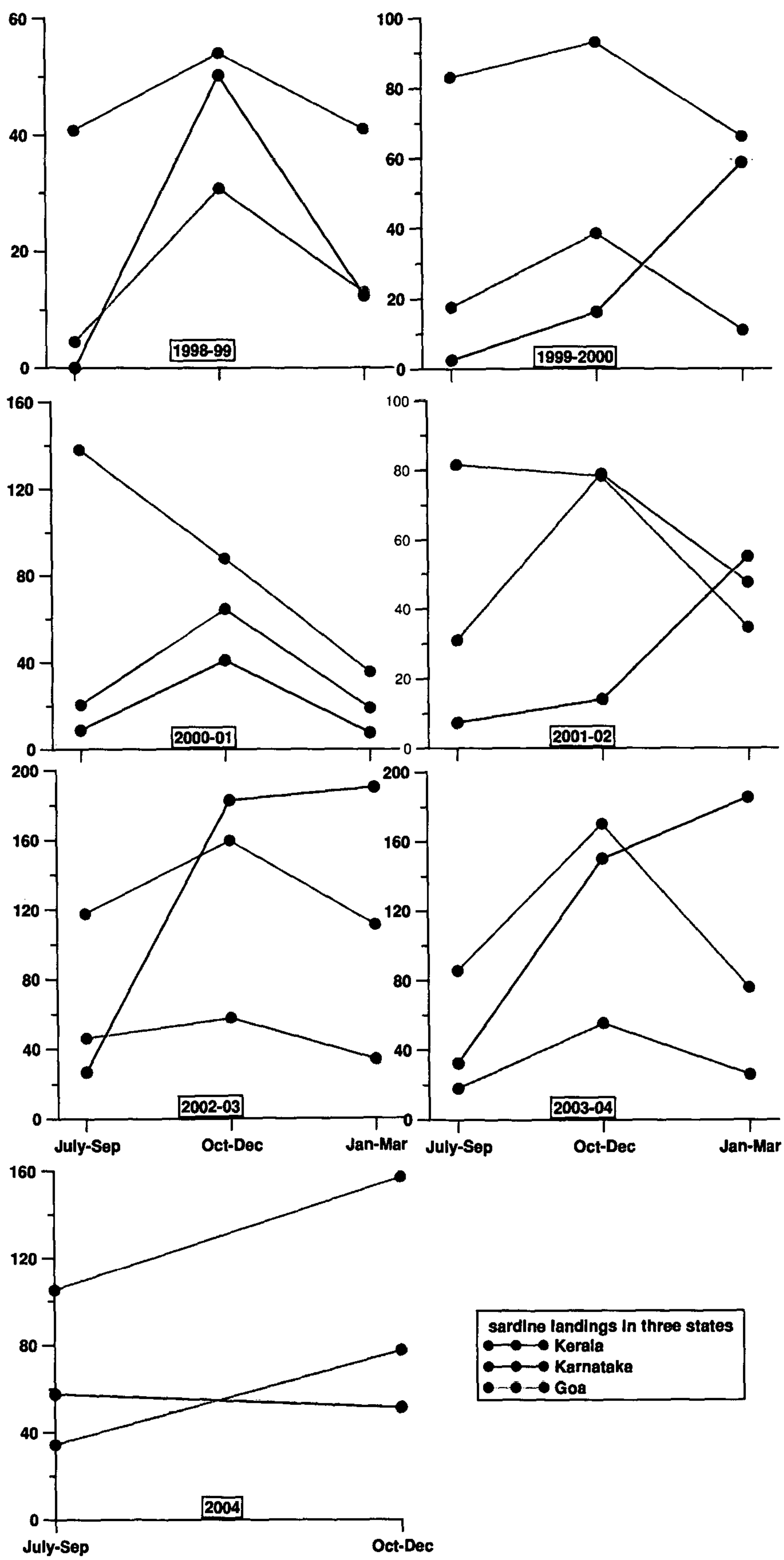


Figure 3.8: Satellite derived chlorophyll off Kerala, Karnataka and Goa during the active breeding season of sardine.


1998-99
1999-2000
2000-01
2001-02
2002-03
2003-04
2004
0
20
40
60
80
100
120
160
200
July-Sep
Oct-Dec
Jan-Mar
sardine landings in three states
Kerala
Karnataka
Goa

to September. This coincides with the high chlorophyll concentration seen during May to September every year. Thus, we find a probable connection between the life history and biology of sardines to phytoplankton bloom dynamics. This supports the finding that the fish itself times its appearance to exploit the productive southwest monsoon period [Madhupratap et al., 1994]. The upwelling bloom can be characterized with respect to its peak amplitude *viz.*, timing of peak, timing of initiation and duration. In this study, magnitude of the bloom during initiation month is considered for characterization of bloom, which naturally falls in the month of May every year. May is the most critical month for sardines because both bloom initiation and the beginning of sardines' active breeding phase occur during this month.

A delay in the initiation of bloom in the area results in hampering the congenial conditions for survival of sardine larvae. In the prevailing rough conditions when fishing activity is slackened, there may be an apparent paucity of sardine. But, as we find in the published reports [Raja, 1969; Longhurst and Wooster, 1990] when there was fishing during July and August, it was noticed that the spawners enter the coastal waters due to increase in food production, and migrated beyond the usual fishing belt (30 m depth) for spawning. The spawners again made a re-entry to compete with the juveniles for feeding. The juveniles enter the coastal waters gradually for feeding during January to March and steadily migrate to deeper waters with reduced food. The disappearance initiates from the north sardine fishing ground and ends up in the southern areas later.

Recent works on the survival and early life history of fishes elucidates various factors including predation, drift pathways and changing environmental conditions in addition to variation in food [Houde, 1987; Miller et al., 1988; Leggett and Deblois, 1994; Cury et al., 2000; Bakun and Broad, 2003]. Upwelling in the waters of the southwest coast of India is restricted to 5 to 15^0N, and the variability in physical parameters is manifested in the chlorophyll intensity [Smitha et al., 2008]. A correlation between available environmental datasets (SST, sea bottom temperature, surface salinity, surface dissolved oxygen, bottom dissolved oxygen, pH, nutrients, chlorophyll, zooplankton, rainfall, multivariate *El Nino* Southern Oscillation index, coastal upwelling index, and derived SST) and sardine catch from the study area vividly segregate the significance of chlorophyll from other environmental factors in explaining the sardine catch from the Malabar upwelling area [Krishnakumar and Bhat, 2008]. A similar analysis of data sets is redundant in the context of this investigation. Hence, this investigation focused on food alone, the lone implicated factor chlorophyll-a (as an index of phytoplankton biomass), and explored various avenues of this factor in explaining sardine variability.

A fine scale spatial and temporal pattern of egg and larval stages of sardines in relation to chlorophyll concentration could have yielded a proper model for describing the presence or absence of sardines in coastal waters within a definite chlorophyll range. There are sparse reports of sardine eggs from Quilandy [Devanesan, 1943b] and Kozhikode [Nair, 1953] and also descriptions of the larval and postlarval stages of sardines in these regions [Nair, 1959]. But the lack of information on the distribution of eggs and larvae emphasizes the need for sampling of early life history stages of sardines over many years for determining the annual condition of larval and juvenile sardines in relation to chlorophyll concentrations.

Chapter 4

Modelling hydrodynamics of Gulf of Kachchh, Goa and Mangalore coastal regions

4.1 Introduction

In chapter 3, the requirement of time series environmental data set in explaining the case of Indian oil sardine larval survival, migration and aggregation is discussed. But, lack of information on the distribution of fish eggs and larvae emphasize the need for data on early life stages of fish, spatially and temporally at high resolution, to demarcate areas of fish abundance. Numerical modelling is an alternate tool to generate environmental and biological datasets, which can be a surrogate for huge data gaps hampering investigations in fisheries biology. Hydrodynamics is the basis for any other processes in the sea, as it explains the forcings required for the processes. The output of hydrodynamic module is given to particle tracking to track the trajectories of particles (larvae) released from a point. Chapters 4 and 5 explain how the numerical modelling results can be used to compare the biological abundance and fish larval transport in three different marine ecosystems namely, the GoK, Mandovi-Zuari and Mangalore. This chapter describes the numerical modelling related to hydrodynamics of the study regions. It includes details of model domain, model set-up, model calibration, sensitivity analysis, model validation for each domain and finally explains the hydrodynamics of each study area which forms the input for studying the larval transport.

4.2 Model set-up

Setting up a model for the simulation of flow needs a suitable computational domain, which permits proper specification of open boundary conditions for water level or fluxes and wind inputs. Bathymetry is specified with respect to Mean Sea Level (MSL). The bed friction is included by using Manning number and eddy viscosity presented by Smagorinsky constant as described in chapter 2. Mean wind speed and direction is used for the GoK region (Table 2.2) and AWS wind data is used for Goa and Mangalore regions as input parameter (Figure 2.1), assuming that wind speed and direction are uniform over the model area in a given time step. The warm-up period is set for a few minutes at the initial level, and hence the model gets stabilized within a few hours.

4.2.1 Model domain

In the GoK, choice of the model domain was supported by the results of a previous study [Babu et al., 2005] which suggests that eddies near the open boundary of the GoK could possibly reduce the flushing rate, and thus substantially increase the residence time of discharged material in the GoK. Hence, bathymetry was represented using a regular rectangular Cartesian grid with spacing of 500 m and was created by extracting depth data from MIKE-CMAP and Naval Hydrographic Office (NHO, Dehra Dun, India) charts. The model domain extends to 180 km and 120 km in X and Y directions respectively (Figure 1.2).

In the Goa region, two different model domains were set up with coarse and fine resolution rectangular Cartesian grids of 500 m * 500 m and 50 m * 50 m spacings, respectively. Bathymetry data has been linearly interpolated to each grid in the model domain. The coarse resolution domain extends 110 km and 140 km in the X and Y directions, respectively (Figure 1.4). This domain is used for studying the larval dispersion along the coast. However, this coarse domain is inadequate to resolve some specific details at certain areas, especially inside the estuary. Hence, a fine resolution domain, which extends to 13 km and 14 km in X and Y directions, respectively (Figure 1.4), has been considered to simulate hydrodynamics and larval transport inside the estuary.

For the Mangalore region, the coastal stretch is shorter compared to the previous studies. Hence, a model bathymetry of 200 m * 200 m regular rectangular Cartesian grid has been created. The model domain extends 65 km and 50 km in the X and Y directions, respectively (Figure 1.5).

4.2.2 Time step and length of simulation

The time step interval (Δt) for the simulation has been selected in such a way that it should satisfy the stability criterion. The values of Δt and duration of the simulation for the study region are listed below:

(i) GoK Considering the irregular bathymetry, a time step of 18 s has been selected and this yielded a Courant number of 1.01. Simulations are carried out for a specific period, representing the rspective seasons as given below:

   (a) April 2002 (Pre monsoon)
   (b) 17 June 2002 to 4 July 2002 (SW monsoon)
   (c) November 2002 (NE monsoon).

(ii) Goa: Time steps of 20 s and 15 s were considered in the coarse and fine models, respectively. The corresponding Courant numbers are 3.6 and 1.7, respectively. The higher Δt in the large domain helps to reduce the computational time, as large set of simulations have been setup for larval transport in this domain. The smaller Δt applied in the small domain is primarily to satisfy the stability criterion as the selected grid size is small. Simulations are carried out for three different seasons as given below:

   (a) December 2006 (NE monsoon)
   (b) April to May 2007 (Pre monsoon)
   (c) October 2007 (Post monsoon).

(iii) Mangalore: Since the coastal stretch is smooth with less obstructions, a time step of 10 s is selected and the corresponding Courant number is 1.14. Model simulations are carried out for three different seasons as given below:

   (a) December 2006 (NE monsoon)
   (b) April to May 2007 (Pre monsoon)
   (c) October 2007 (Post monsoon).

4.3 Model calibration

Model calibration could be carried out by adjusting Manning number, eddy viscosity or wind friction factor. Eddy viscosity, K is an empirical constant that typically ranges between 0.01 and 0.06 [DHI, 2001]. A wind friction value of 0.0026 was applied as a constant in time and space for the model domain. Similar values were followed by the researchers Babu [2005]; Jahfer-Sharif [2009] and Vinod-Kumar [2010] for hydrodynamic model studies along the west coast of India. The details of model calibration are as given below:

4.3.1 Calibration using Manning number

Varying bed resistance has been applied by changing the Manning number (as discusssed in chapter 2) to calibrate the model. Thereafter, a uniform Manning number of 32 $m^{-3}.s^{-1}$ was applied throughout the GoK domain and this reproduced accurate tide variations all along the GoK. The statistical analysis between modelled and measured water levels and current components at locations off Okha, Mid-channel and Kukadsar yielded a good correlation with less bias (Table 4.1). However, a constant Manning number was not found to be suitable for Goa and Mangalore regions as the simulation blown-up at some of the open boundaries. It has also been found that a Manning number of 32 $m^{-3}.s^{-1}$ could not reproduce the accurate tide variations as the bottom features are different from that of GoK. Hence, a variable bed resistance file has been created with low Manning number ($\leq$ 10 $m^{-3}.s^{-1}$)) at the open boundaries and high Manning number (25 to 60 $m^{-3}.s^{-1}$) at narrow channels according to the bottom roughness of the region. Hence, two different resistance files (calibrated) have been applied for actual simulations in Goa and Mangalore regions. The use of bed resistance file reduced the stability problems and provided better output as seen in the comparisons at Captain of Ports jetty in Goa region and Suratkal in Mangalore region (Table 4.1). Close match and positive correlation (r$\geq$0.43) between modelled and measured data at different locations across the model domain (Table 4.1) indicate that the model is able to reproduce water level and currents accurately in the entire model domain of respective study area.

Table 4.1 Quality indices used for comparing model results with current measurements and tides at locations along the entire model domain illustrating reproducibility of proper flow fields

Parameter	Location	Component	Bias	RMS	Corr.coeff.
Current speed		u	0.04	0.18	0.87
$(m.s^{-1})$	Off Okha	v	0.07	0.17	0.91
Water level (m)			0.06	0.39	0.87
Current speed		u	-0.01	0.15	0.98
$(m.s^{-1})$	mid-channel GoK	v	0.00	0.09	0.09
Water level (m)			0.10	0.50	0.84
Current speed		u	0.08	0.15	0.95
$(m.s^{-1})$	Off Kukadsar	v	0.06	0.15	0.92
Water level (m)			-2.00	2.08	0.94
Current speed		u	0.16	0.37	0.71
$(m.s^{-1})$	Captain of Ports jetty	v	-0.06	0.14	0.68
Water level (m)			-0.14	0.15	0.99
Current speed		u	-0.01	0.03	0.43
$(m.s^{-1})$	Off Suratkal	v	-0.05	0.10	0.65
Water level (m)			0.01	0.02	1.00

4.3.2 Calibration using Eddy viscosity

The Smagorinsky constant is used to damp out numerical oscillations and stabilize the model. The Smagorinsky constant is initially set to 0.4 $m^2.s^{-1}$. But, the best fitting of the model simulation to the measured parameters is achieved by setting it to 0.5 $m^2.s^{-1}$. Hence, this value has been applied as the calibration factor in actual simulation.

4.4 Model validation for flow pattern

The validation process gives an indication of the model sensitivity and confidence that the results it produced are consistent with measurements. Recording current meter (model: RCM7; make: Aanderaa, Norway) data, measured during the study period, were used for model validation. Comparison between measured and modelled u and v components of the current show good match. The discrepancies may be due to depth-averaged conditions simulated by the model. The modelled water level at select stations also show very close agreement with the measured/predicted water level, indicating that the model is well calibrated for the study regions (Figures 4.1, 4.2 and 4.3). Scatter plots (Figures 4.4, 4.5 and 4.6) between measured and modelled water level, zonal (u) and meridional (v) currents show that how the model is reasonably reproducing the accurate hydrodynamics of the study regions.

4.4.1 Gulf of Kachchh

Correlation coefficients of 0.59 and 0.54 have been obtained between measured and modelled ebb and flood velocities, respectively. There is slight over-estimation of modeled flow velocities for ebb and flood, with a bias of 0.06 and 0.12 ms^{-1}, respectively. The $R.M.S.$ error observed for ebb and flood velocities are 0.18 ms^{-1} and 0.25 ms^{-1}, respectively. The modelled and predicted water levels show a very good match with no phase difference. Table 2 indicates that the model reproduces water level and currents accurately in the entire model domain. Results show strong u-component and weak v-component in the GoK. Seasonal changes in the flow patterns in the GoK were simulated (Table 4.2) for three different seasons, namely, pre monsoon (April 2002), SW monsoon (June 2002) and NE monsoon (November 2002).

4.4.2 Goa coastal region

Model results have been validated with measurements carried out during 14 November to 10 December, 2007 (Figure 4.2). The modelled and predicted water levels show a very good match with no phase difference. The modelled u and v-velocities show good match with the measured current velocities. Correlation coefficients of 0.71 and 0.68 have been obtained between measured and modelled u and v-velocities, respectively. A slight over-estimation of the modelled u-velocity has been noticed, with a bias of 0.16 $m.s^{-1}$. The modelled v-velocity is slightly under-estimated, with a bias of -0.06 $m.s^{-1}$. The $R.M.S.$ error observed for u and v-velocities are 0.37 $m.s^{-1}$ and 0.14 $m.s^{-1}$, respectively.

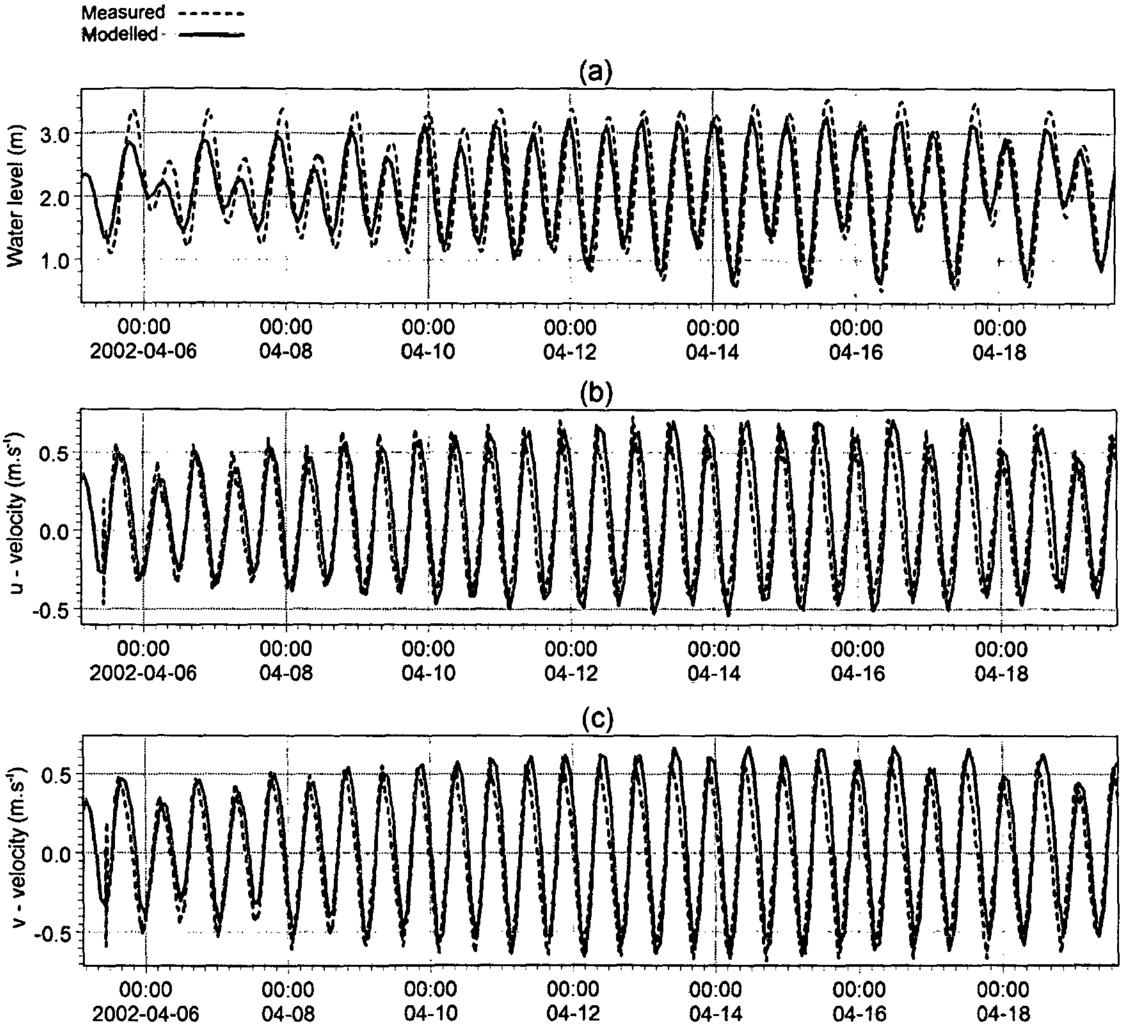


Figure 4.1: Comparison between measured and modelled water level and current off GoK: (a) water level, (b)u velocity and (c) v velocity

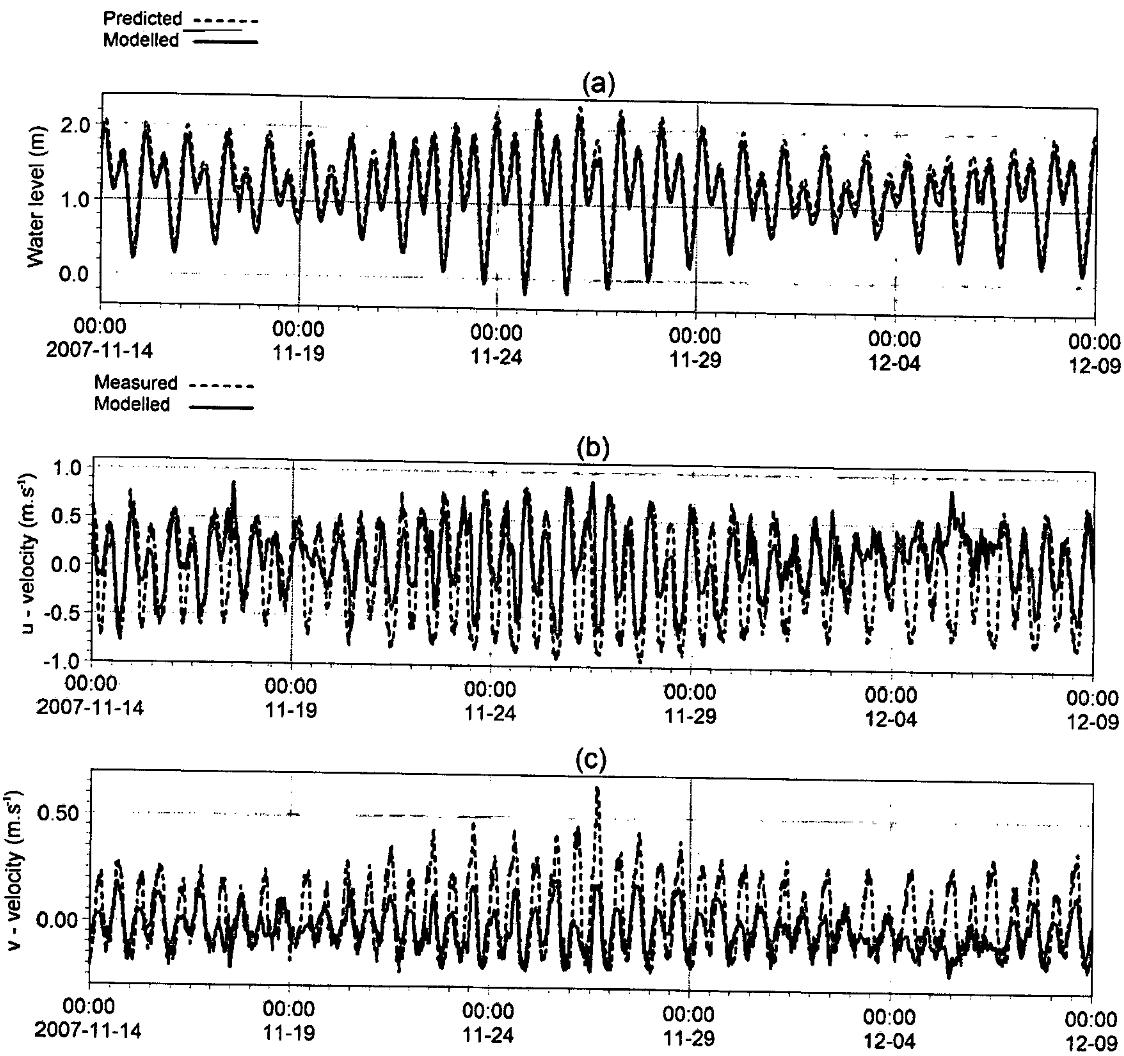


Figure 4.2: Comparison between measured and modelled water level and current off Captain of Ports: (a) water level, (b)u velocity and (c) v velocity

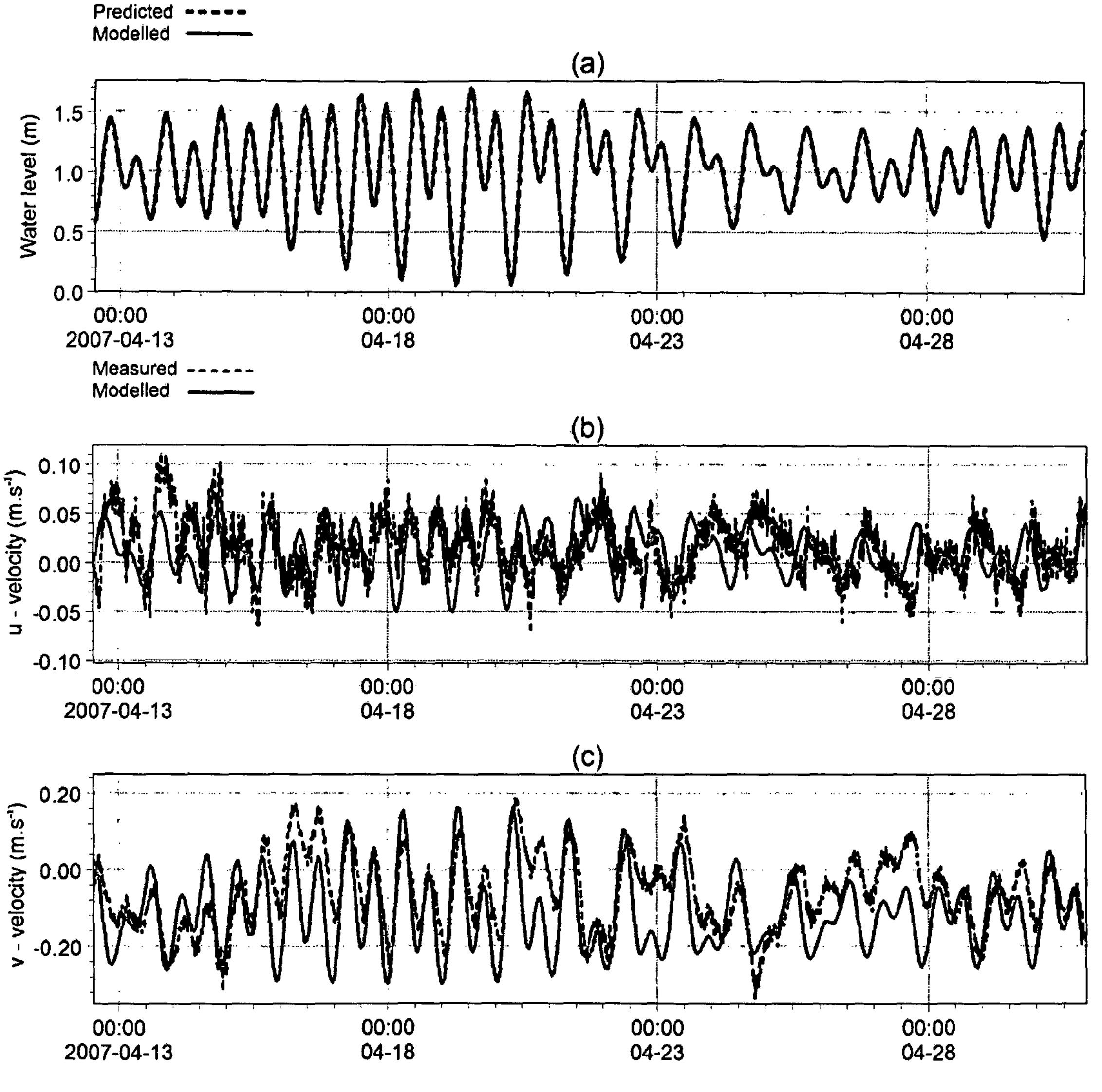


Figure 4.3: Comparison between measured and modelled water level and current off Suratkal: (a) water level, (b)u velocity and (c) v velocity

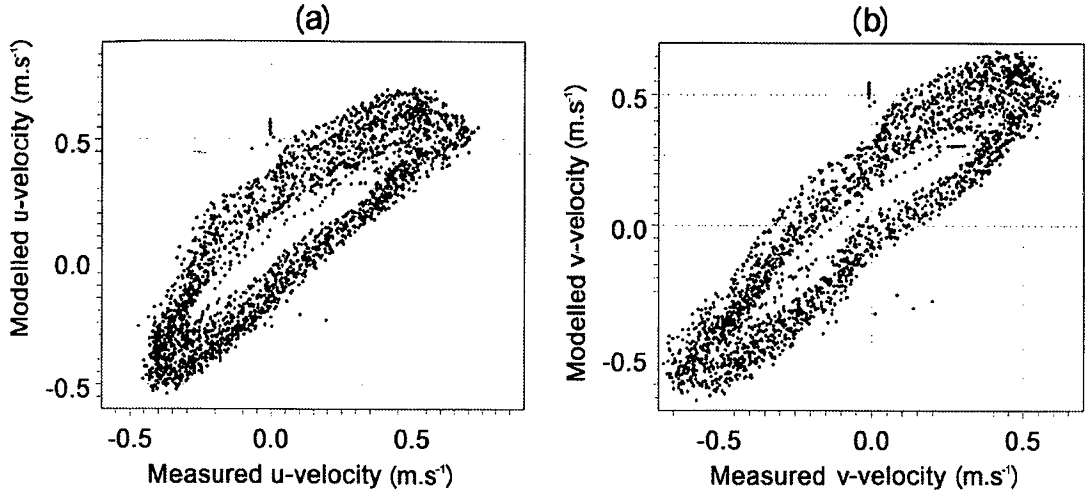


Figure 4.4: Scatter showing measured and modelled currents off Okha: (a) u-velocity and (b) v-velocity

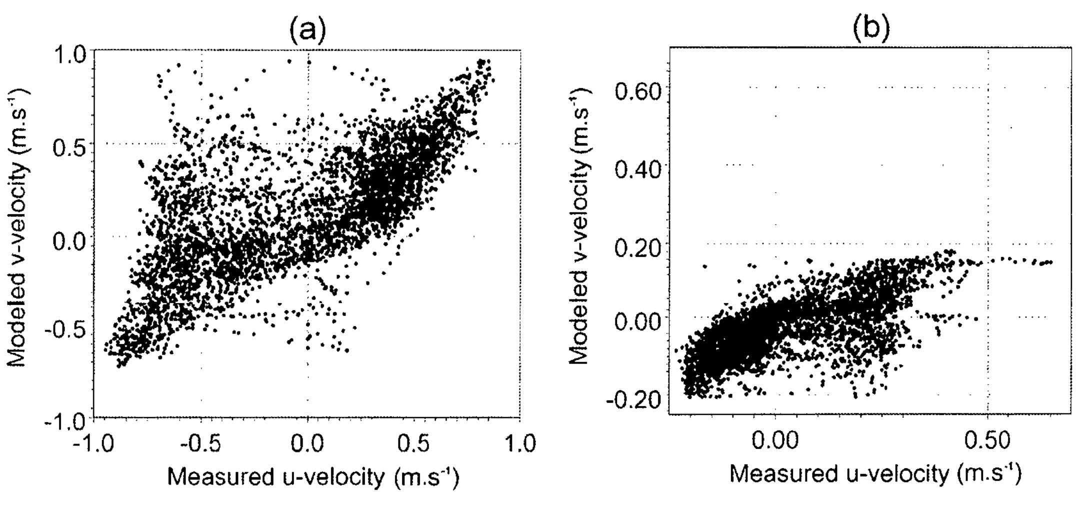


Figure 4.5: Scatter showing measured and modelled currents off Captain of Ports jetty: u-velocity and v-velocity

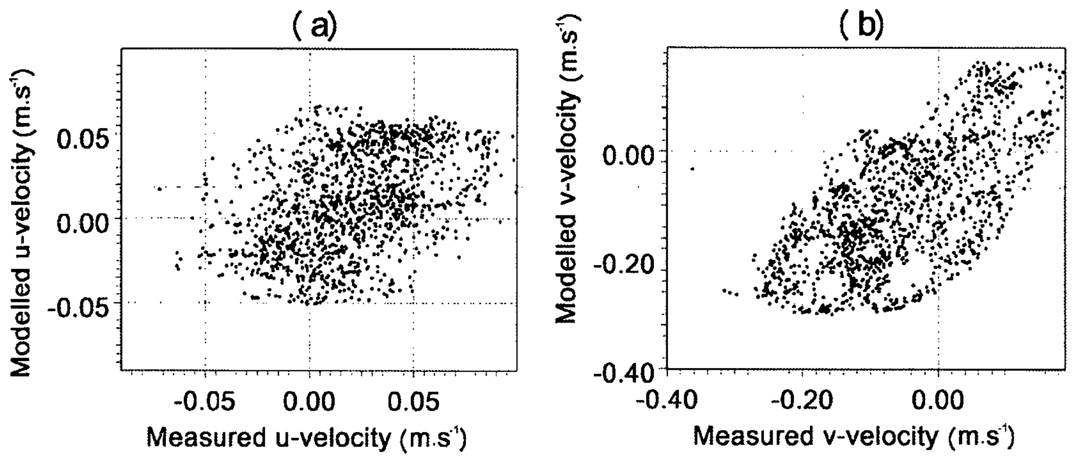


Figure 4.6: Scatter showing measured and modelled currents off Suratkal: u-velocity and v-velocity

4.4.3 Mangalore coastal region

Model results have been validated with measurements carried out during 14 November to 10 December, 2007 (Figure 4.3). The modelled and predicted water levels show a very good match with no phase difference. The modelled u and v-velocities show good match with the measured current velocities. Correlation coefficients of 0.43 and 0.65 have been obtained between measured and modelled u and v-velocities, respectively. A slight underestimation of the modelled u and v-velocity has been noticed, with a bias of -0.01 $m.s^{-1}$ and -0.05 $m.s^{-1}$ respectively. The $R.M.S.$ error observed for u and v-velocities are 0.03 $m.s^{-1}$ and 0.10 $m.s^{-1}$, respectively.

4.5 Flow patterns in the study regions

Water levels and flow patterns have been analyzed for each study regions for different seasons and the results are discussed below.

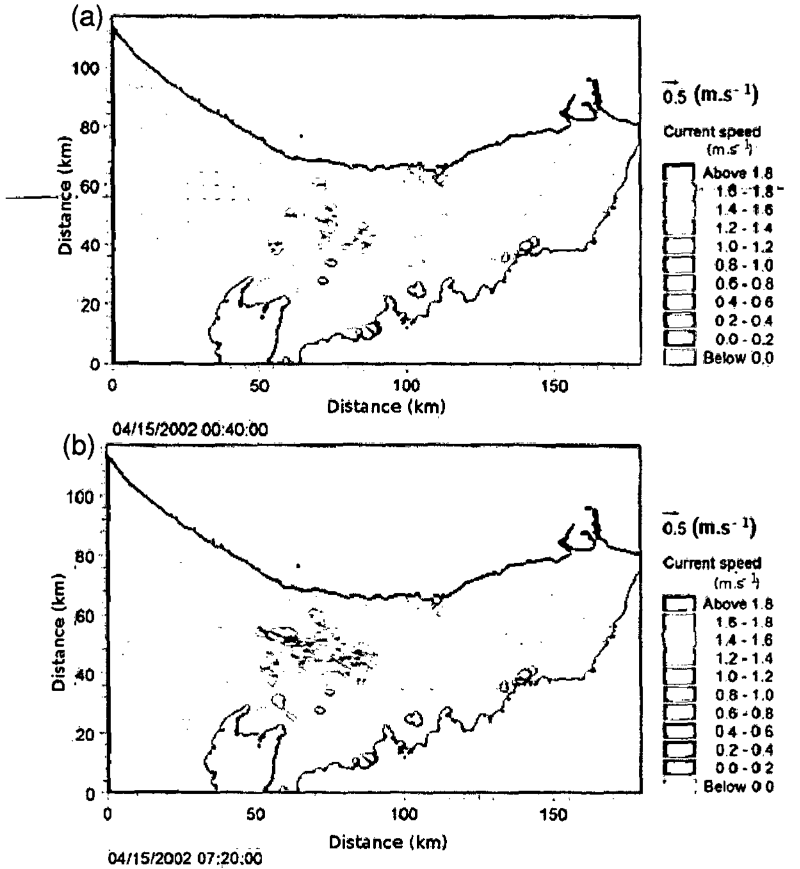


Figure 4.7: Typical current patterns off Okha (April 2002) on a spring tide: (a) during flood and (b) during ebb

4.5.1 Gulf of Kachchh

For the GoK region, the flow pattern during pre monsoon (April 2002), SW monsoon (June 2002) and NE monsoon (November 2002) are simulated and presented (Table 4.2). The model results show that tidal currents control the circulation. The major currents go from the mouth to the head of the Gulf in the ENE direction during flood and WSW during ebb, with relatively high currents along the central Gulf (Figure 4.7). The geometry of the Gulf is such that the entry of water during flood is through the southern side and pushes the water inside.Thereafter, the flow is deflected towards north as the width drops at the mid-Gulf and coastal orientation changes from the mid-Gulf to the head. During ebb the outward flow is mostly along the northern rim of the Gulf. A cross-section of the flow pattern during different seasons at Okha, mid-channel and Kukadsar (Table 4.2) indicate 50 to 80% higher current speed in the mid-channel compared to Okha (at the Gulf mouth) and Kukadsar (at the Gulf head). The residual velocity is important in understanding the transport of eggs or larvae discharged in a coastal environment. Residual velocity is driven by density gradients and tides. Since the GoK is a well mixed basin, density gradient contribution to the residual current is ignored and tide induced residual currents are analysed. The residual velocity field computed from the model results confirmed the existence of three distinct permanent eddies with diameter varying between 10 and 20 km in the western half of the gulf, an anti-cyclonic eddy south of Ranwara shoal, a cyclonic eddy east of it and another anti-cyclonic eddy located between the cyclonic eddy and the investigator reef [Vethamony et al., 2004; Babu et al., 2005]. Thus in the eastern half of the Gulf, the circulation shows a net transport towards Kandla (along the northern rim of the Gulf) which induces the clockwise circulation. On the contrary, in the western Gulf, it is anti-clockwise. It is evident hat the net transport from the open ocean into the Gulf is primarily through the southern side of the mouth, and the net outward transport is through the northern side.

Table 4.2 Characteristic flow pattern for different seasons in the GoK

Season	Current	Off Okha				Mid-channel				Off Kukadsar			
		Max.current speed($m.s^{-1}$)		Pre-dominant dir(^oN)		Max.current speed($m.s^{-1}$)		Pre-dominant dir(^oN)		Max.current speed($m.s^{-1}$)		Pre-dominant dir(^oN)	
		Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood
Pre-monsoon	measured	0.80	0.94	210	50	1.37	1.35	265	90	0.86	0.87	235	55
	modelled	0.89	1.06	210	45	1.63	1.64	265	90	0.87	0.77	230	50
SW-monsoon	measured	No measurements during this season											
	modelled	0.74	0.99	225	45	1.06	1.09	275	105	0.89	1.3	340	140
NE-monsoon	measured	1.4	1.2	260	95	1.88	1.67	260	100	1.28	0.91	240	55
	modelled	1.4	1.2	270	90	1.19	0.94	270	105	0.81	1.3	340	140

During pre monsoon, the winds are weak and consistently in the westerly direction. The model simulated tidal currents during spring ebb and flood show an apparent increase in the u component by about 10% in the absence of wind forcing. However, during neap, the tidal currents show a reduction upto 20% compared to the measured currents, suggesting that wind forcing is more effective during neap than spring phase [Vethamony and Babu, 2010].

4.5.2 Goa coastal region

For the Goa region, the flow pattern during NE monsoon (December 2006), pre monsoon (May 2007) and post monsoon (October 2007) are simulated and presented (Table 4.3). The flow along the Goa coast is towards north while flooding and towards south while ebbing, with a prominent southward drift during pre monsoon and NE monsoon seasons. However, during post monsoon season, the prominent drift is towards north. In the Mandovi-Zuari estuarine system, the flow is towards east while flooding and towards west while ebbing. The tidal currents play major role in the cross-shore movement of the particles in the estuarine systems. However, small scale tidal eddies also influence the dispersion characteristics inside the estuary. The flow is relatively higher inside the Mandovi river. The maximum current speeds at the COP while flooding are 0.96, 0.88 and 0.70 ms^{-1} during pre monsoon, post monsoon and NE monsoon seasons, respectively, whereas they are 0.89, 1.08 and 0.65 ms^{-1} respectively, while ebbing. The maximum current speeds inside the Zuari estuary (at the larval sampling point) while flooding are 0.3, 0.63 and 0.12 ms^{-1} during pre monsoon, post monsoon and NE monsoon seasons, respectively, whereas they are 0.33, 0.39 and 0.20 ms^{-1} respectively, while ebbing.

Table 4.3 Characteristic flow pattern for different seasons in the Mandovi estuary

Season	Current	Sampling point (near Dona Paula)				Off Goa				Off COP			
		Max.current speed($m.s^{-1}$)		Pre-dominant dir(^oN)		Max.current speed(ms^{-1})		Pre-dominant dir(^oN)		Max.current speed($m.s^{-1}$)		pre-dominant dir(^oN)	
		Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood
Pre-monsoon	modelled	0.33	0.30	265	110	0.15	0.21	315	135	0.89	0.96	285	105
	measured	No measurements during this season											
Post-monsoon	modelled	0.39	0.63	265	115	0.26	0.17	320	120	1.3	0.92	285	115
	measured	No measurements at sampling point and off Goa								1.08	0.88	290	103
NE-monsoon	modelled	0.20	0.12	275	95	0.23	0.25	305	125	0.65	0.70	295	115
	measured	No measurements during this season											

A cross section of current speed and direction show that flood currents from the mouth of the estuaries to the head are relatively stronger at narrow stretches of the estuary (Figure 4.8). During SW monsoon season, currents are influenced by the fresh water discharges and this factor was also taken into account in the model simulation. The Hydrodynamic simulation indicates that the coastal water flows into the estuary from the north and flushes out of the estuary towards the south. At the mouth of the estuary, the northward flow takes a cyclonic reversal and flows again southwards without entering the estuary. Thus in general it can be inferred that the flow is controlled by the semi-diurnal tides and reversing seasonal wind patterns to a greater extent. There is an effect of the sea breeze too in the circulation process. The current movement is faster in the narrow channels of the estuarine head. The freshwater influx makes it a fresh water pool in the upstream of the estuary during the SW monsoon and practically remains sea water for the rest of the season in the downstream.

4.5.3 Mangalore coastal region

For the Mangalore region, the flow pattern during NE monsoon (December 2006), pre monsoon (May 2007) and post monsoon (October 2007) are simulated and presented (Table 4.4). Tidal currents are significant in this region. The current speed during ebb tide

Table 4.4 Characteristic flow pattern for different seasons in Mangalore region

Season	Current	Off Mulki				Off Suratkal			
		Max.current speed(ms^{-1})		Pre-dominant dir(^oN)		Max.current speed(ms^{-1})		Pre-dominant dir(^oN)	
		Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood
Pre-	measured	No measurements off Mulki				0.40	0.30	170	360
monsoon	modelled	0.13	0.19	335	165	0.30	0.17	180	350
Post-	measured	No measurements during this season							
monsoon	modelled	0.14	0.28	335	160	0.30	0.17	180	350
NE-	measured	No measurements during this season							
monsoon	modelled	0.17	0.41	330	160	0.28	0.29	180	90

is stronger than the flood tide since the wind driven currents are also in the same direc-

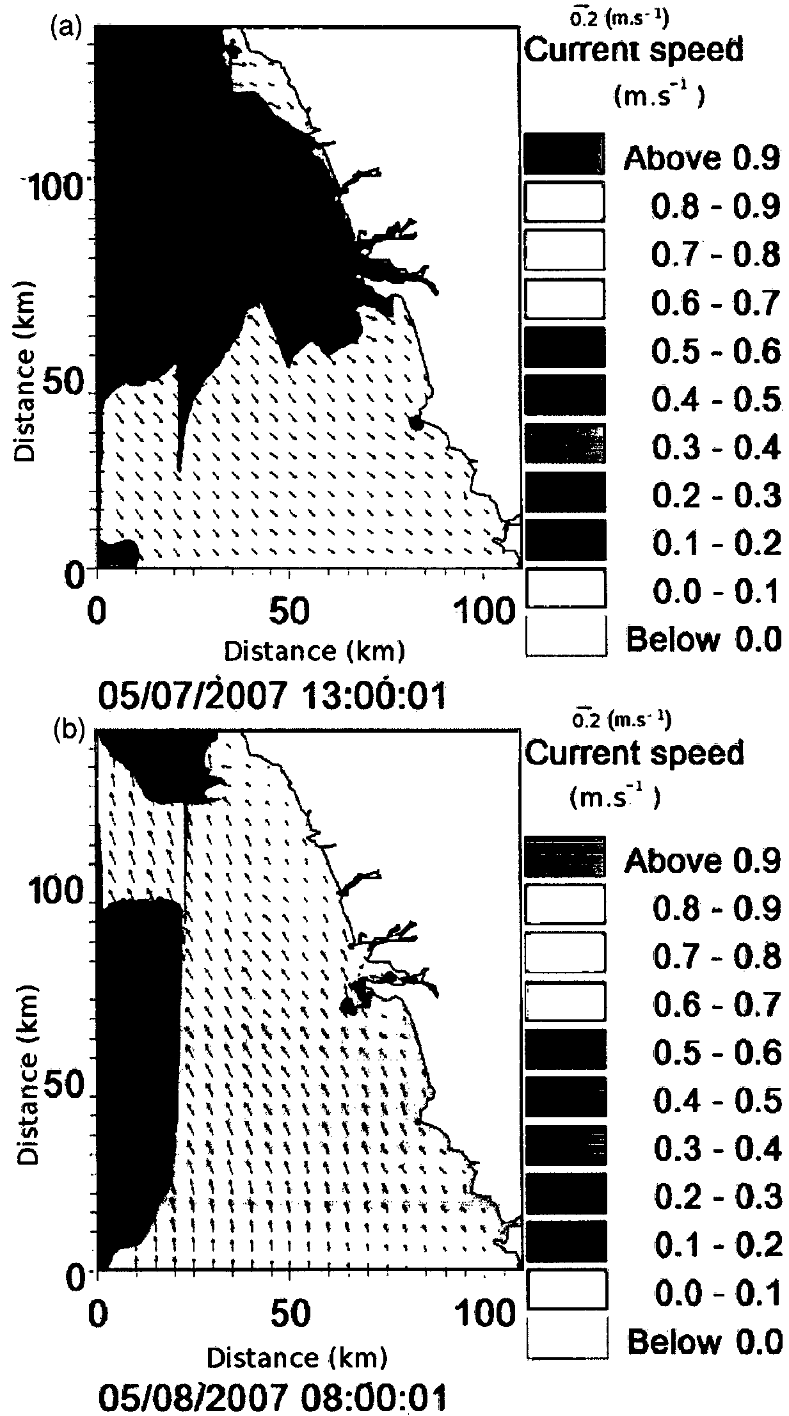


Figure 4.8: Typical current patterns in the Mandovi-Zuari during (April 2006) on a spring tide: (a) during flood and (b) during ebb (

tion. During ebb tide, the predominant flow is towards south and during flood the flow is towards north. Tidal currents oscillate mainly in the longshore direction with little net cross-shore current. The onshore and offshore currents (u-component) were meager compared to the alongshore currents (v-component), irrespective of the period of simulation. The current slows down during the tidal slack, that is, just before current reversal takes place. There will be no contribution by the fresh water discharges during NE monsoon period, but we can expect some contribution during SW monsoon period, but that will be very minimal. The simulated current shows that the currents are having distinct variability corresponding to the tide. In general, the current speed remains low $\leq$0.3 $m.s^{-1}$ usually, except during spring tide when current speed reaches a range of 0.5-0.7 $m.s^{-1}$ at the narrow estuarine mouth of River Netravati (Figure 4.9). The simulations indicate that the orientation of the main axis of the current flow as NW-SE during both the seasons. The current vectors were also split into N-S and E-W components (Figure 4.9). The N-S components were influenced by tides. They oscillated with a semi-diurnal frequency. The E-W components were affected mostly by winds. The eastward component was comparitively stronger than the westward component. The coastal flow off Mangalore could be considered as reversing tidal currents flowing more or less parallel to the coast with an onshore drift under the influence of the existing wind pattern.

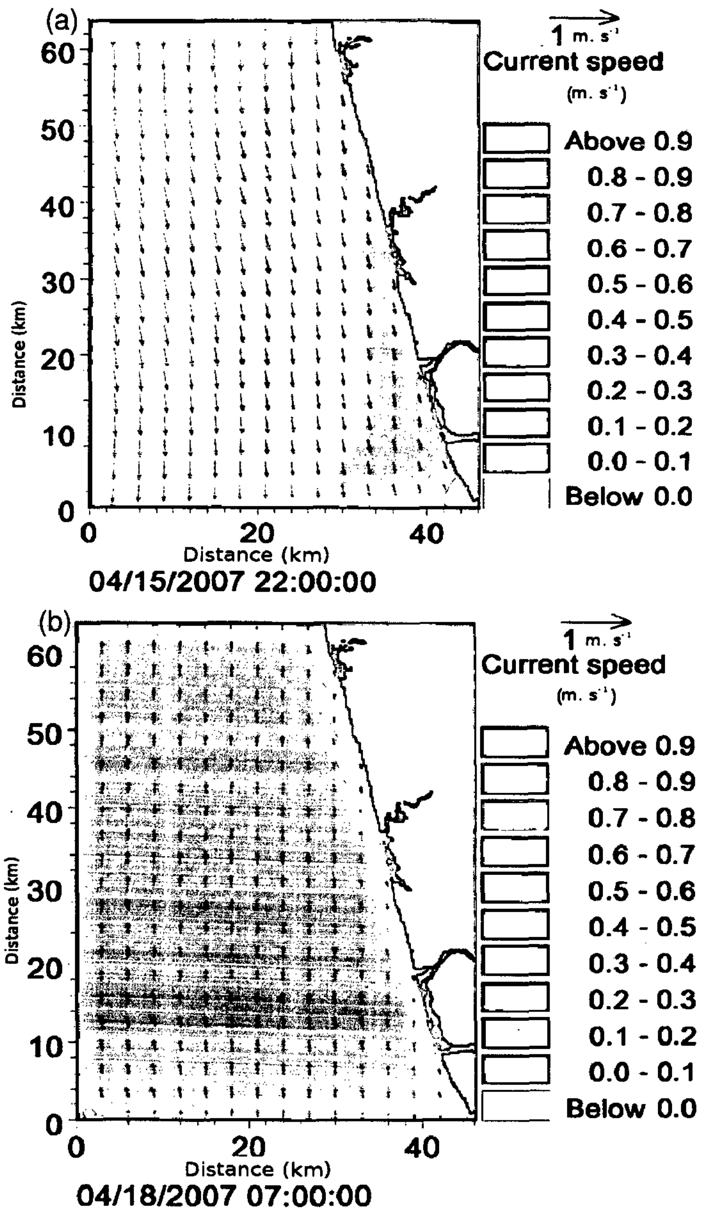


Figure 4.9: Typical current patterns off Mangalore (April 2006) on a spring tide: (a) during flood and (b) during ebb

Chapter 5

Larval transport in three different marine ecosystems

5.1 Introduction

For the domains discussed in chapter 4, fish and shell fish larval transport has been studied using hydrodynamic and particle tracking models. Management of fisheries along the coastal waters of India are carried out on the archetype that local fisheries is well mixed with the open waters, and closed areas are enforced as a protective measure for prospective nursery areas of fish [Singh, 2003]. But, there is always the possibility of a self recruitment of fish taking place in these waters which was not established in any of the earlier field studies. The irregular coastline of WCI along with its shoals and reefs may trap water and inert particles. A sufficient retention time in a basin could retain fish larvae [Lobel and Robinson, 1986], zooplankton [Boicourt, 1982; Sammarco and Andrews, 1988; Murdoch, 1989; Thiebaut et al., 1994], phytoplankton [Roff et al., 1979] and other neutrally buoyant material [Wolanski and Hamner, 1988; Black et al., 1990] in this area. The pelagic larval phase of fishes/ shell-fishes are responsible for their dispersion or retention [Cowen and Sponaugle, 2009], and during this phase larvae are considered as "poor swimmers" [Leis et al., 2006a] when the hydrodynamic forcing on the larvae exceeds its swimming ability, but there are proven cases where larval behaviour has influenced dispersal trajectories [Chia et al., 1984; James et al., 2002; Cowen et al., 2006; Aiken et al., 2007].

The scale and predictability of measured fish larval dispersion or retention remain unknown largely due to the difficulty in measuring dispersion in open marine environments. Utilization of high-resolution biophysical models in estimating dispersal distances or retention time is advantageous as the models allow multiple releases of virtual eggs/ spawn, thus making each individual simulation equivalent to numerous observations of dispersal event. These virtual observations provide information about expected variability in hydrodynamics and allow construction of a connectivity matrix [Cowen and Sponaugle, 2009].

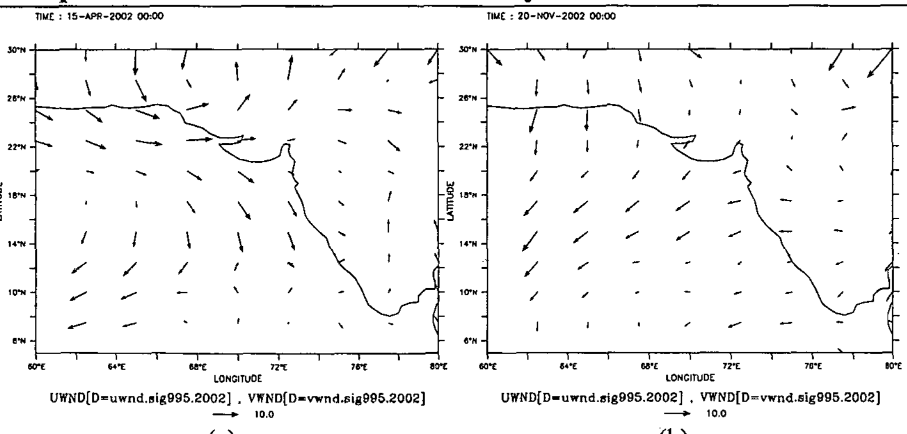
A common strategy employed in this kind of model is to predict the maximum likelihood of retention of investigated species based on habitat attributes [Guisan and Zimmermann, 2000; Moisen et al., 2006; Elith and Graham, 2009]. Numerical modelling of fish eggs dispersion at the Patos Lagoon estuary in Brazil was carried out by Martins et al. [2007] using similar methodology.

No work has been carried out so far in the coastal waters of India to determine the influence of physical forcing on fish/shell-fish larvae under which they are widely dispersed or locally retained. One of the objectives of this study is to find out whether the abundant fish population in the GoK and Mangalore as well as the barnacle population in Mandovi-Zuari estuary is the manifestation of self recruitment by the adult population trapped due to hydrodynamic or geographical barriers. In this study, eggs/ spawn are released as inert conservative particles from their representative spawning sites under a range of hydrodynamic and associated dispersion processes unique to the study areas to simulate the spreading of eggs/ spawn and transport of larvae. The percentage likelihood of retention/ dispersal of larvae from spawning sites have been quantified.

5.2 Fish larval transport in a semi-enclosed basin: the Gulf of Kachchh

5.2.1 Background

Mangrove and coral reef ecosystems are the spawning and nursery grounds for a majority of fishes in the tropical coastal waters [Chittaro et al., 2004]. The last two decades witnessed rampant destruction of coral reefs and mangrove ecosystem due to anthropogenic pressures and climate change [Chittaro et al., 2004; Mumby et al., 2004]. Degradation of these ecosystems resulted in reduced recruitment of fish worldwide [Rogers and Beets, 2001] and it is not very different in the GoK. GoK is famous for its fisheries potential [Vijayalakshmi et al., 1993]. Establishment of industries close to the coast resulted in destruction of flora and fauna, which are closely associated with the spawning and larval



(a) (b)

Figure 5.1: Wind pattern in the GoK region: (a) during NE monsoon and (b) during pre monsoon season

rearing cycle of fishes [Vijayalakshmi, 2002]. Larvae are treated as passive particles, and are released from the spawning sites which are decided based on a field survey in the GoK.

5.2.2 Spawning behaviour of fish in GoK

The spawning sites surveyed for fish egg abundance (Table 5.1) were along the coasts, and away from the influence of strong currents *viz.*, mid-channel and eddies of the Gulf. Particles released from sites A, B, E and F (Figure 5.3) experienced wider dispersal pattern than at sites C and D. Hence, the sites A, B, E and F have been selected as spawning sites. During NE monsoon, eggs are retained in the southern GoK due to predominant winds from NNW (340^o) (Figure 5.1) ruling out the importance of spawning sites at E and F. Our field surveys also indicated higher egg abundance at sites B and F during NE and pre monsoon seasons, and these sites are showing wider dispersal patterns (Table 5.1). Based on these considerations, the spawning sites at B and F have been chosen for egg release. Site A was selected for all the three seasons as particle trajectory revealed dispersal in all the three seasons when particles were released and tracked from this site. Thus, particles were released from two sites (F and A during pre monsoon and SW monsoon and B and A during NE monsoon). Since egg abundance data were not available for SW monsoon season, spawning sites were assumed to be the same as pre monsoon period. Primary nursery areas are those areas in the estuarine system where initial post-larval development takes place. These areas are usually located in the uppermost sections of a system, where populations are uniformly very early juveniles. In this study, nursery areas are defined as those areas where $\leq$30% likelihood of retention of larvae is simulated (Figure 5.4). The numerical experiments show that these nursery areas are distributed in the ecologically sensitive regions (Figure 1.3) along the GoK, except for the northwestern part of the Gulf.

5.2.3 Fish larval dispersion/retention

(i) Pre-monsoon: There was uniform dispersal of particles along the northern and southern boundaries of GoK in the pre monsoon season (April), and less than 20% of particles exited along the northern boundary to the open waters. The number of exited particles is negligible in comparison to the spread along the boundaries of GoK (Figure 5.2). The particles dispersed along the southern boundaries remained within the domain. Thus, it can be inferred from the numerical experiment that the fish eggs released along the southern boundaries of the gulf tend to remain in the region, whereas the eggs from spawning sites in the northern gulf does not remain within the gulf. The northwestern boundary of the gulf near spawning site F is a crucial nursery ground during pre monsoon and SW monsoon seasons. But, this area is not regulated for fishing. Fish egg abundance survey also corroborates the numerical simulation.

(ii) SW monsoon: Particle trajectories were simulated for this season to observe the influence of SW monsoon (June) on fish larval transport. The particles were dispersed from the spawning sites predominantly south of GoK. Those released in the north being retained with larger larval retention on the reefs (Figure 5.2) in contrast to a wider dispersal as seen during pre monsoon season. Less than 10% of larvae exited the domain during the SW monsoon season. The westward movement of larvae is restricted by the predominant SW winds, and hence only a small percentage of larvae exited the domain. Similar to pre monsoon season, the particles dispersed along the southern boundaries remained within the domain.

(iii) NE monsoon: The particle dispersal during the NE monsoon (November) followed the pattern of previous seasons for the station close to Okha (site A). But, at station close to B, the particle release showed retention in and around the release site without much dispersal (Figure 5.2). Less than 10% of the particles exited the domain as in the case of SW monsoon season. Retention of larvae is higher at the spawning site B beacause B is surrounded by shoals, where currents are relatively weaker– a favourable condition for accumulation.

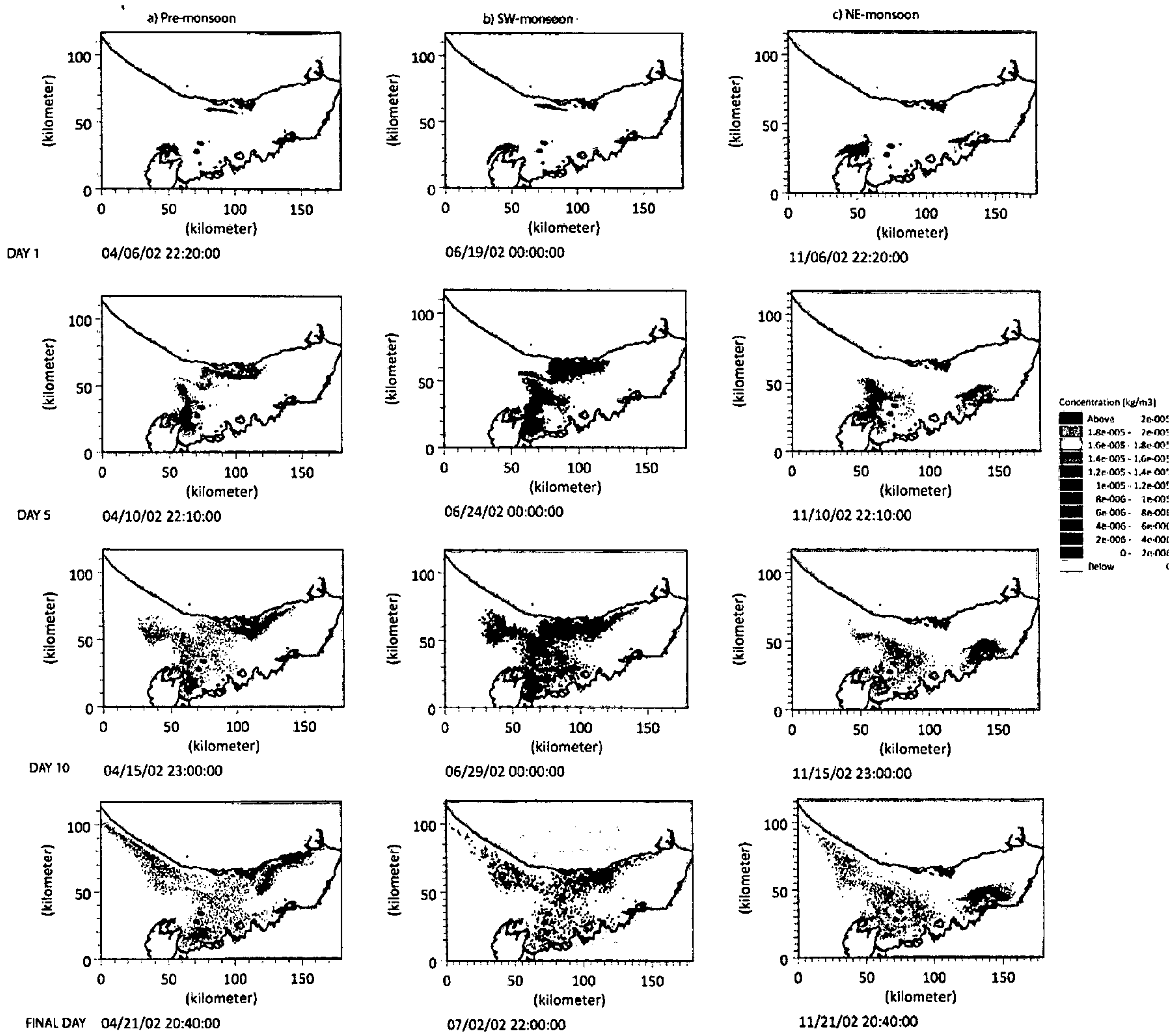


Figure 5.2: Simulation of larval dispersal on day 1, 5, 10 and 16 in the GoK: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon

Table 5.1 Fish egg abundance (in numbers) and site ecology as observed during exploratory surveys during April and Novemeber, 2002

Site	Place	Fish egg abundance April 2002	Fish egg abundance November 2002	Site ecology	Geographical barrier	Remarks
A	off Okha	0	114	uneven topography with strong currents.	free flushing in and out with ebb and flood.	less commercial fishing operations.
B	off Bedi	60	3177	scattered reef and mangrove areas along the coast	small islands and reefs in the Marine National Park; weak currents	commercial fishing operations active.
C	off Navalakhi	454	60	closer to the land area and depth gradually reduces to the minimum	extreme SE boundary with a tide variation of 7.31 m	only port in Rajkot district with some fishing activities
D	off Kandla	35	0	alluvial marshy tidal flats with a major creek system	high tidal movements and unusually strong currents	less fishing except shore based hand and gill net
E	off Kukadsar	0	0	4 streams, 2 shoals and a couple of islands visited by flamingoes	presence of tapering land and shoals restrict flood and ebb flows	fishing by trawlers
F	off Mandvi	140	8	river Rukmanathi joins this site	river run-off less	fishing grounds with increasing efforts

5.2.4 Redistribution of the fish larvae to nursery grounds

Particles move along with the tidal currents, which is the dominant hydrodynamic force in the GoK. Since eddies are present in the western region of the GoK, *i.e.* near the open boundary, it is possible that these eddies could effectively reduce the flushing rate, and thus substantially increase the residence time of discharged materials in the GoK [Babu et al., 2005]. Ebb currents promote less than 10-20% of the accumulated particles to escape out of the domain along the northern boundary without entering into the eddy region (Figure 5.2). The particles redistributed along the southern Gulf remained in the region without being flushed out.

In general, particles released at the GoK mouth were pushed along with flood currents into the Gulf. This particle dispersion suggests that the fish eggs after hatching may be dispersed into northern and southern boundaries, rich in reefs and mangroves. However, during pre monsoon season their entry and exit were partially prevented by the residual eddies at the gulf-mouth, and this is evident in the particle trajectories (Figure 5.3). The flow pattern in the GoK can be visualized like a concentric circle with maximum currents in the mid-gulf and minimum towards the periphery (Figure 4.7). It is observed that the particles, which are released in the inner Gulf moved further into the eastern Gulf. Simulation experiment was repeated after releasing the particles during flood and ebb tides. The transport of particles is highly variable with time and space in accordance with tides and currents. Across the Gulf and along the Gulf, maximum excursion of particles is seen during pre monsoon season. In general, it can be inferred that the spawned fish egg and hatched-out larvae are retained in the GoK domain when released in the interior stations, close to the eastern boundary of the Gulf.

Trawler catch data at various sampling points suggest abundance of fish in the southern GoK region (Figure 5.5). This possibly could be explained as an outcome of excess fish larval retention in the southern gulf. The numerical simulation also corroborates maximum particle retention in the southern gulf in comparison to the northern gulf. In the northern Gulf, 10-20% of the redistributed particles escaped along the northern boundary. In the GoK, spawning sites may vary with seasons, but the dispersal of larvae occurs in

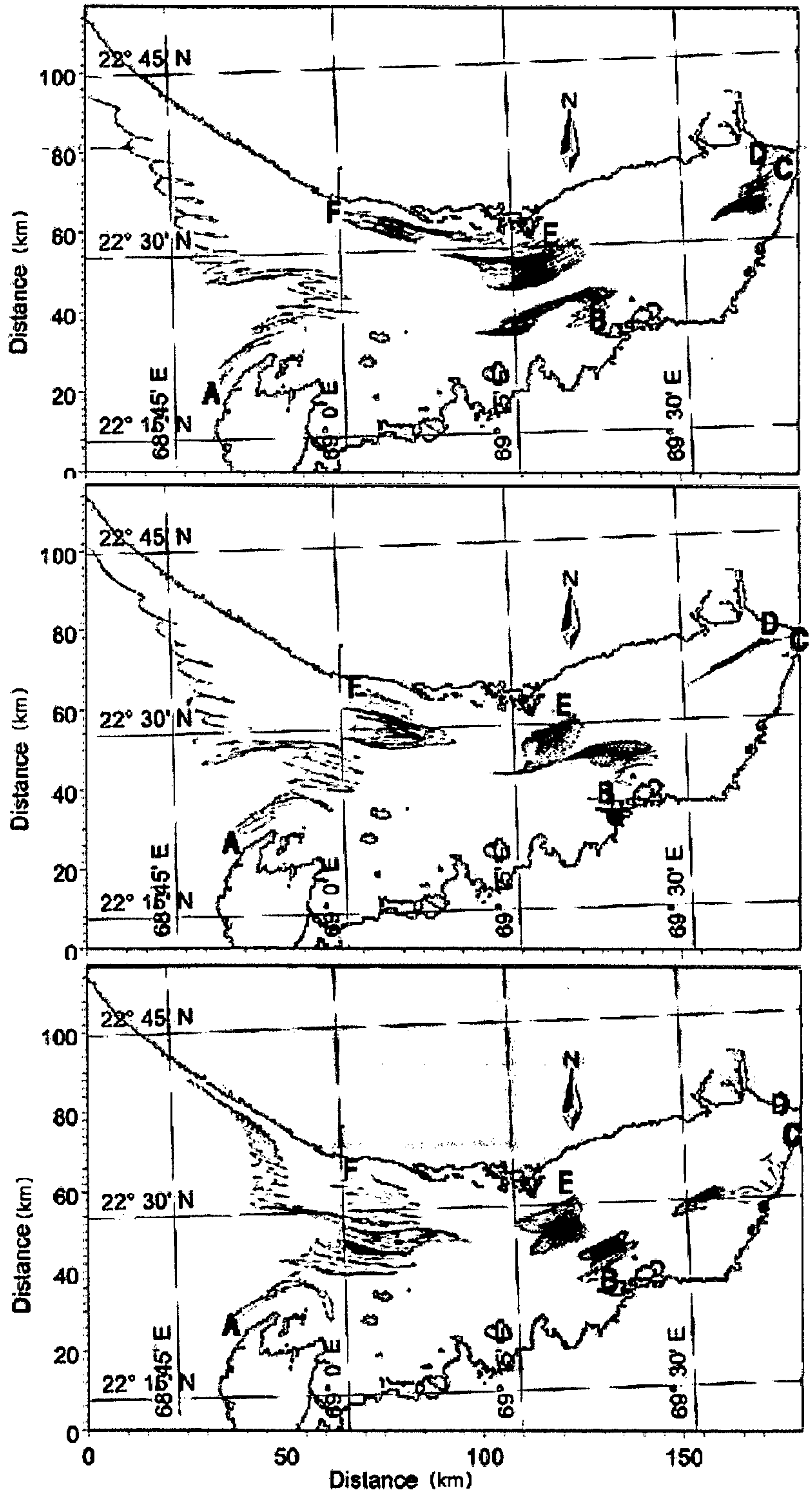


Figure 5.3: Simulation of particle trajectories from various sampling stations: A-off okha, B-off Bedi, C-off Navlakhi, D-off Kandla, E-off Kukadsar, and F-off Mandvi: (a) April 2002 (b) June 2002 and (c) November 2002

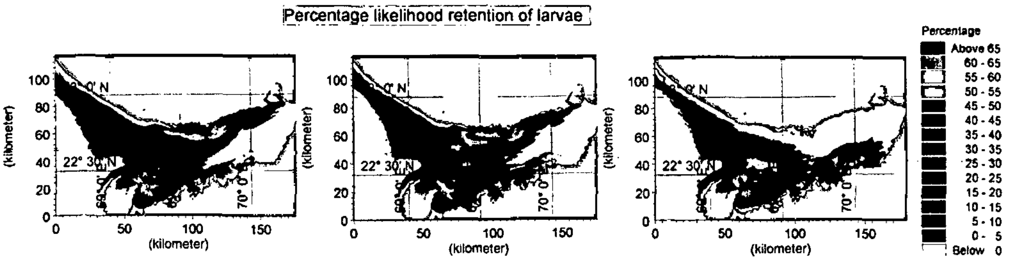


Figure 5.4: Simulation of likelihood of retention of fish larvae in the GoK during: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon

such a way that larvae reach nursery grounds in the GoK rather than being dispersed in the open ocean off GoK.

Even though geographical barriers are imperative in larval retention, their role is superseded by the local hydrodynamics in the GoK. The particle dispersions from the same spawning site showed variations with changes in hydrodynamic conditions (Figure 5.3). The abundance of fish along the southern region is a clear indication of a driving force which redistributes the fish larvae to ecologically sensitive mangrove and reef areas in the GoK. Thus, the model simulation of particle transport in the GoK reiterates the fact (known biologically) that larval aggregations are going to occur in the southern GoK during active breeding phase of fishes with varying dispersal pattern from the spawning sites. The fish larval abundance in the GoK is qualitatively inferred and the accuracy of modelled particle with the larvae at field level cannot be quantified on real time basis. But, the results definitely indicate the effectiveness of this tool.

Larval movements of icthyoplankton can be simulated as they are passive, and drift along with the prevailing currents. But juvenile fishes after planktonic phase cannot be traced with the help of current movements as they acquire swimming speeds that are able to counter the currents. Predation, productivity changes, fishing effort and environmental changes will affect the abundance pattern which is not incorporated in the numerical model. In protected areas like a gulf, the areas of likelihood of retention of planktonic larvae may have an impact on the fish abundance as the nursery areas can also become their possible rearing grounds. But, there are uncertainties involved in this hypothesis. However, a proper demarcation of potential nursery grounds is definitely an outcome of these modelling studies (Figure 5.2). Protecting these nursery areas as a part of the fishery management measure may improve the fish abundance, and also juvenile fish retained in a productive area tend to remain in the same area. The existing fisheries management strategy in the GoK is based on demarcation of the ecologically significant sites, which is not flawless. There are possibilities of nursery grounds shifting from ecologically significant sites due to changes in hydrodynamic patterns. This limitation can be rectified when nursery ground locations are identified based on likelihood of retention areas from a validated numerical model. This study corroborates not only the ecologically significant sites prioritized by fishes (Figure 1.3), but also a few additional nursery grounds generated from the model (Figure 5.2) and confirmed in the field.

The seasonal changes in spawning sites by fish may be an adapted strategy in the GoK to cope up with the changes in current pattern to advect the eggs from a safe spawning site to a productive rearing area in the GoK. A lot of uncertainties are involved in explaining this assumption, but the observations are evident enough to prove this changing pattern. The calibrations required for a model to estimate the water quality and productivity of a semi-enclosed coastal environment is complicated as suggested in a previous study along the western coastal waters of India [Menon, 2004]. The present study invokes the idea that the demarcation of marine protected areas should be based on the rationale that areas of maximum likelihood of retention of icthyoplankton will be a better fisheries management strategy for the GoK, imbibing the concepts of an ecosystem-based spatially structured approach.

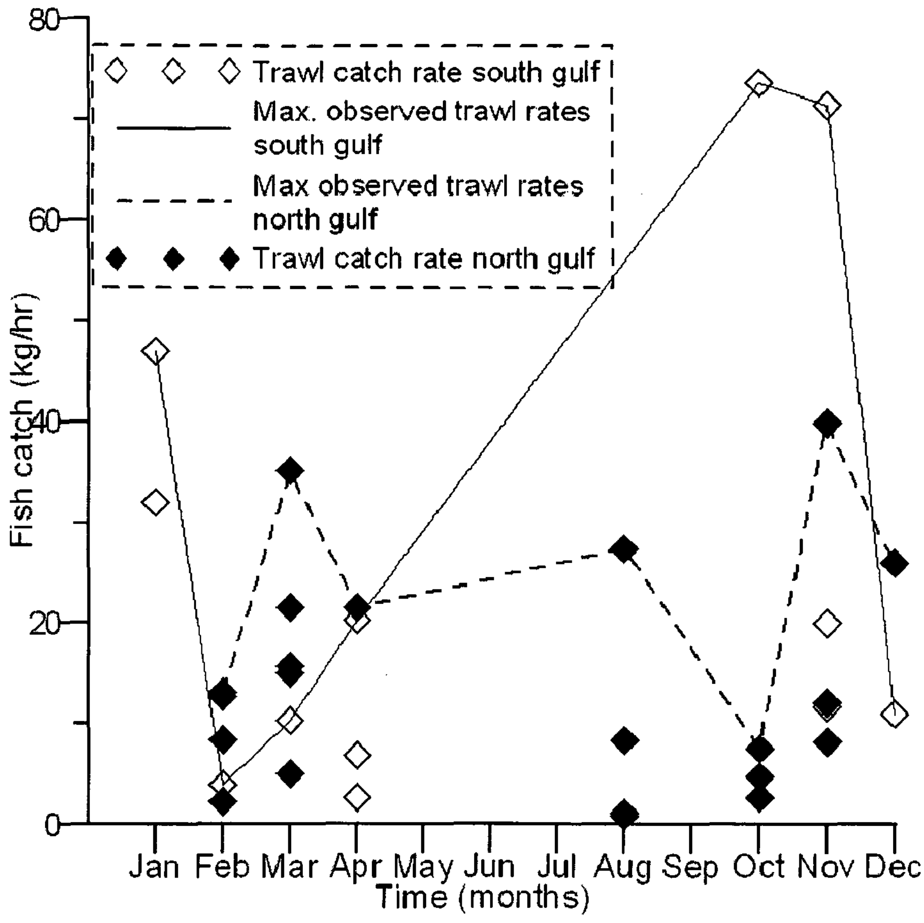


Figure 5.5: Trawl catch variation in the northern and southern GoK

5.3 Barnacle larval transport in an estuarine system: Mandovi-Zuari

5.3.1 Background

Biofouling by barnacles poses a major threat to navigation, fishing, tourism and port related activities in the Mandovi-Zuari estuarine system. The life cycle of many fouling and benthic suspension feeding organisms includes a pelagic larval phase important in dispersal. The key factor that influences the final destination of the larvae during dispersal is their Planktonic Larval Duration (PLD) phase, which depends on both genetic and environmental variables. In the barnacles, a number of planktotrophic naupliar stages culminate into cyprid which is the competent stage for settlement on a suitable hard substratum. *Balanus amphitrite*, Darwin, an acorn barnacle, is the dominant intertidal and fouling organism in the Mandovi-Zuari estuarine system [Anil, 1986; Desai and Anil, 2005]. The larval phase of *Balanus amphitrite* includes six planktotrophic naupliar stages, followed by a pre-settling and non-feeding cypris larva [Anil, 1991; Anil et al., 2001]. A characterization based on the quantity of food during planktonic life may indicate the approximate duration of larval life.

The factors such as larval sinking rate, larval swimming speed and direction and velocity of ambient currents play a major role in their dispersal. Environmental (*e.g.* temperature and salinity) or biological, (*e.g.* availability and quality of sestonic food or predation) factors are also imperative in their survival, and influence the length of the larval life. The dispersion of larvae critically depend on ambient currents, as magnitude of currents is often larger than their swimming or sinking velocities. The scales of relevance, in both time and space, are very broad and may include the effects of molecular and turbulent diffusion, tides, storm-mixing events and wind driven currents, internal waves, mesoscale eddies and large scale general circulation [A.Okubo, 1994].

In estuaries, freshwater is mixed with seawater by the action of tides, wind effects and other physical processes. Density differences between seawater and river water may also result in horizontal pressure gradients which affect the flow patterns [Dyer, 1979]. Concerning larval dispersion in estuaries, the most important physical feature(in both salt wedge and partially mixed estuaries) is that the bottom water has a net landward movement and surface water seaward when averaged over a number of tides.

The scale of dispersal depends on movement of the water masses, larval behaviour and duration of pelagic stages. Larval longevity and water movement establish the potential for dispersal, whereas larval behaviour often determines the actual degree of spread. Two independent methods have been employed to estimate the quantitative relationship between duration of the pelagic period and scale of dispersal. Extension of geographic ranges in species with pelagic larvae and sedentary or sessile adults suggest that a 10 to 15 day larval period results in a spread of over 20 to 30 km. This is in agreement with oceanic diffusion measurements and the data suggested a positive correlation between time and spread [Pineda, 2000]. It has been indicated that several hours of larval period results in spread of the order of hundreds of meters, 1 to 2 days allow dispersal of approximately a kilometer, a week or two increases the scale to 10 km, 1 to 2 months correspond to 100 km and a year can result in movement of 1000 km. Significantly greater dispersal requires a substantially longer pelagic period, probably of the order of one week.

In the present case-study, the larval retention and dispersal in the Mandovi-Zuari estuarine mouth was carried out. This study is motivated by the member-vagrant hypothesis that the larval dispersion and retention pattern in the region are maintained by the areas (geographical and hydrodynamic) that limit the dispersal and advection of larvae during the PLD phase. No study has been carried out in the central west coast of India so far to determine the influence of geographic and hydrodynamic limitations on dispersal or retention of barnacle larvae. The focus is to find out whether the abundant barnacle population in Mandovi-Zuari estuarine system is a manifestation of a closed group trapped by the hydrodynamic or geographical limitation.

5.3.2 Barnacle larval abundance

Larval abundance was at its highest peak during October 2007 sampling (Figure 5.6). The abundance significantly differed between all the three sampling periods (Analysis of

Variance $(ANOVA): p \leq 0.0005$). There was an hourly variation in the larval abundance during May 2007 and October 2007 samplings. During December 2006 sampling, larval abundance peaked between 2330 and 0230 hours with a non-significant variation between different sampling hours ($ANOVA: p \geq 0.05$). During May 2007 sampling, more larvae were observed during early morning hours (0230 to 0830 hours) with significant variation between different sampling hours ($ANOVA: p \leq 0.05$). During October 2007 sampling, two peaks in larval abundance were observed during 1730 and 0130 hours. However, from the first peak to the second peak the naupliar density was found to be considerably high. Analysis of variance also showed a significant variation between different sampling hours ($ANOVA: p \leq 0.05$) during this sampling period. A general observation was that the naupliar density increased with tidal amplitude. The number of cyprids in the study region was less compared to the nauplii (Figure 5.6).

5.3.3 Barnacle larval dispersion and retention

The results of larval dispersion simulation carried out in the large domain were analysed for assessing the larval dispersion from the possible spawning locations by calculating the number of larvae reaching the sampling point. The extent of larval dispersion is influenced by winds, tides and currents of the respective seasons as described below:

(i) NE monsoon period: Though tide generated currents are dominant, NE winds have significant role in the larval dispersion and transport during December. A net southward flow along the coast has been observed for the particle transport from all the spawning locations (Figure 5.7). However, the quantum of particles reaching the sampling point at Zuari estuary is in the decreasing order from Arambol to Mormugao. There is no effect in the sampling point at Zuari estuary for the particles released at locations further south of Mormugao Port. The mouth of the Mandovi-Zuari estuarine system is more exposed to NE winds, hence a net off-shore particle transport has been observed for the larvae at Singuirim and Dona Paula. Major amount of particles has been settled along the coastal belt south of Bogmalo for the spawning locations southward from Singuirim.

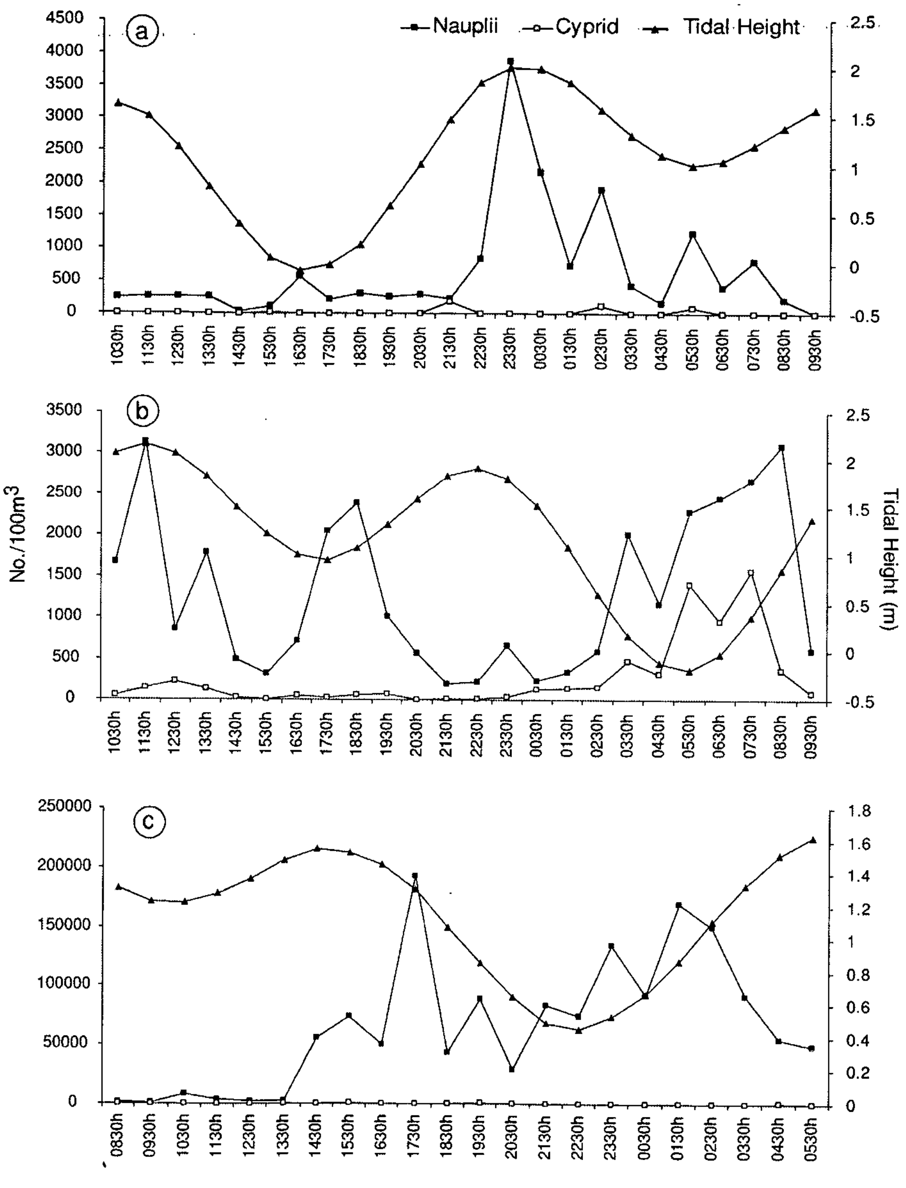


Figure 5.6: Larval abundance noted during the sampling survey in Mandovi and Zuari

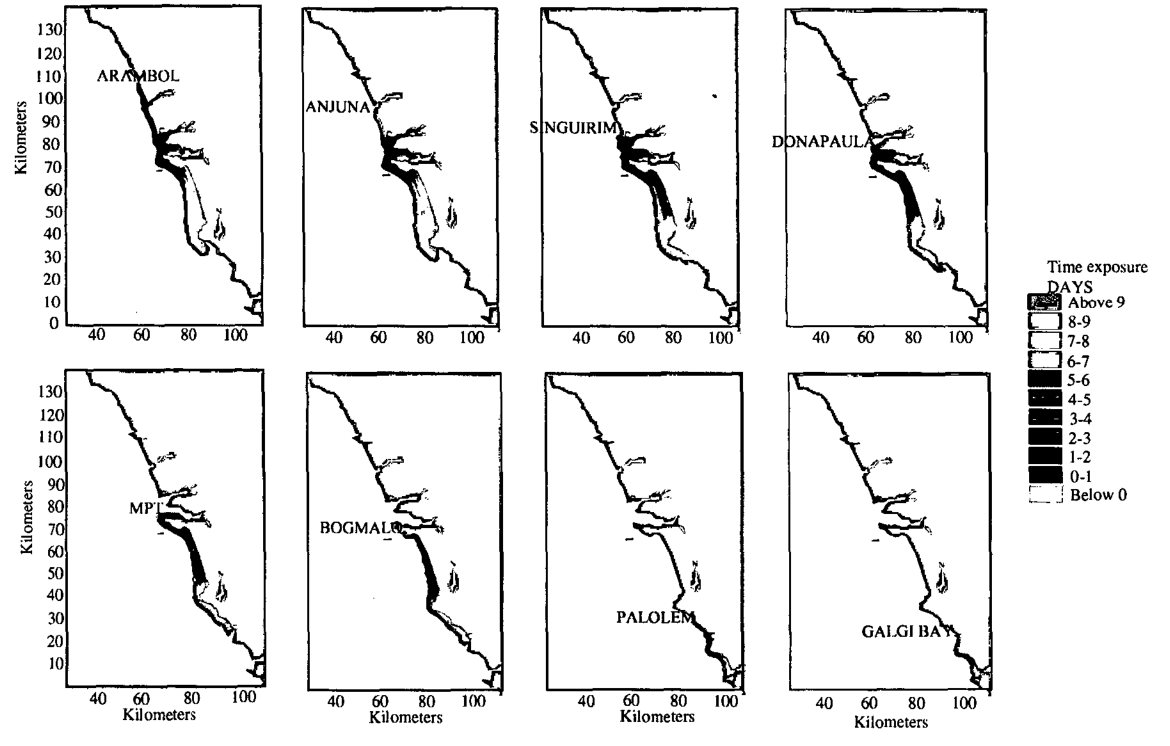


Figure 5.7: Barnacle larval transport during NE monsoon period along the coastal stretch of Goa

(ii) Pre-monsoon period: Sea breeze is prevalent along the west coast of India during pre monsoon season [Aparna et al., 2005] and it has significant impact on the diurnal cycle of the sea-state off Goa [Neetu et al., 2006]. During May, the predominant winds are from northwest and the magnitude is of the order of 5-8 $m.s^{-1}$. This results in a frequent and intense movement of the particles in southward direction and hence, the spread of the larvae is wide-stretched southwards in comparison to December (Fig. 5). The magnitude of southward spread of particles is in the increasing order from Arambol to Galgibagh. However, the quantum of particles reaching the sampling point at Zuari estuary is in the increasing order from spawning locations at Anjuna, Singuirim and Arambol (Table 5.2). There is no effect in the sampling point at Zuari estuary for the particles released at other locations (Figure 5.8).

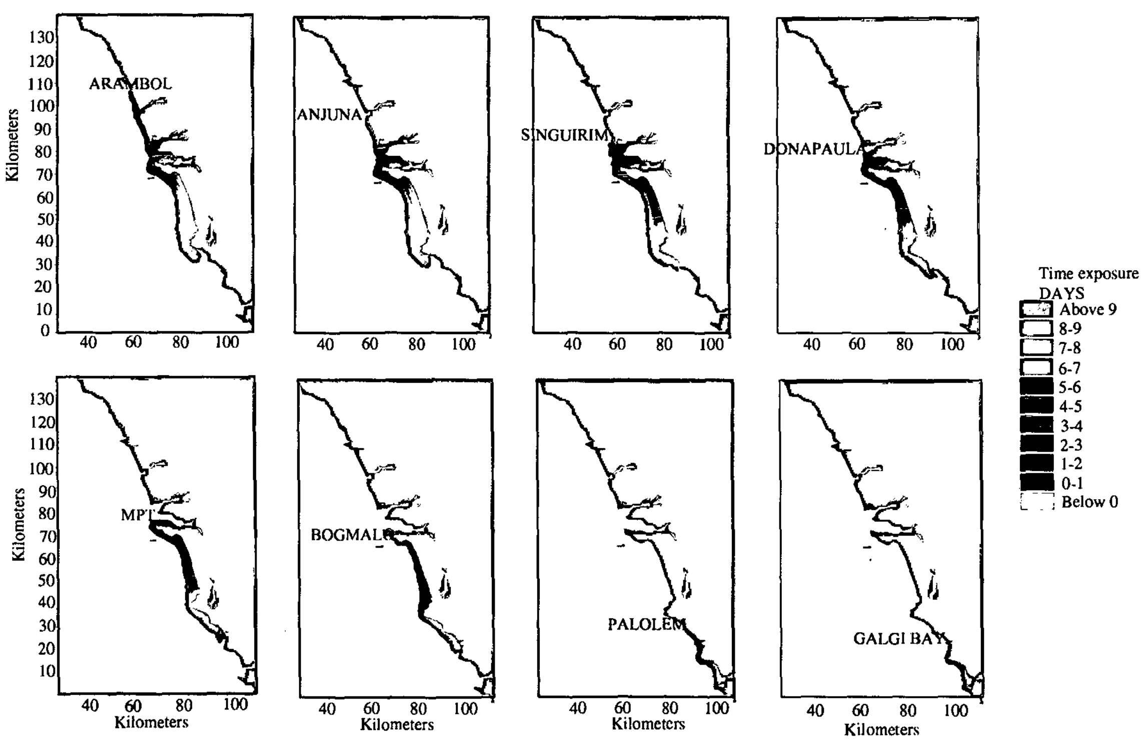


Figure 5.8: Barnacle larval transport during pre monsoon period along the coastal stretch of Goa

(iii) Post-monsoon period: During the first half of October, there exists SW winds with low magnitude due to the retrieval of SW monsoon. However, during the second half, NE winds prevail due to the onset of NE monsoon and the particle movement will be southwards. Therefore, in October dispersal of particle occurs northwards predominantly in the first half and reverses later in the second half (Figure 5.9). The settling of the particles inside the Zuari estuary is considerably less, however it is accumulated near the mouth of the estuarine system. However, the quantum of particles reaching the sampling point at Zuari estuary is in the increasing order from spawning locations at Mormugao Port, Bogmalo and Dona Paula (Table 5.2).

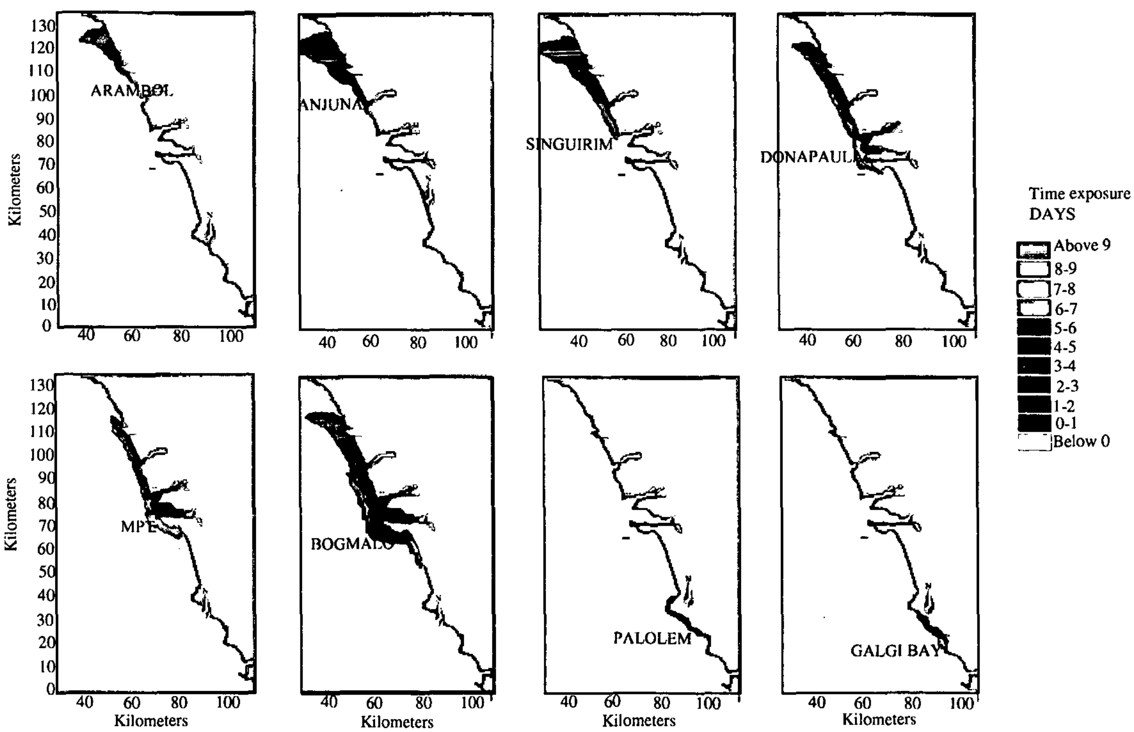


Figure 5.9: Barnacle larval transport during pre monsoon period along the coastal stretch of Goa

There is spatial and temporal variation in the larval dispersal pattern from different spawning sites. The large domain of study vividly indicates a pattern of northern spawning points contributing to larval abundance at sampling point during December and May. But, with the reversing wind and current patterns in October, the larval abundance at sampling point is supported by southern spawning sites (Table 5.2). Larval transport is southward during Dec 06 and May 07, depicting the predominant wind direction.

In October 2007 stations northward upto Singuirim show a northward transport but remaining stations show N-S transport with predominant transport being northward.

Table 5.2 Distance traversed by modelled larvae from major spawning sites along the coastal waters of Goa during Dec 06, May 07 and Oct 07.

Spawning location	Larval dispersal in km (direction)		
	Dec 2006	May 2007	October 2007
Arambol	38(S)	78(S)	22(N)
Anjuna	32(S)	64(S)	35(N)
Singuirim	25(S)	57(S)	42(N)
Dona Paula	25(S)	56(S)	45(N) and 13(S)
MPT	17 (S)	53(S)	43(N) and 16(S)
Bogmalo	26(S)	46(S)	50(N) and 16(S)
Palolem	14(S)	24(S)	10(N) and 6(S)
Galgibagh	10(S)	16(S)	12(N) and 2(S)

5.3.4 Modelled and observed barnacle larval retention

The results of the partcles dispersion simulation carried out in the fine resolution domain (Figures 5.10, 5.11, 5.12) indicate least retention of particles in the estuary during pre monsoon period. This is in concurrence with the observed field data too. There is higher abundance of larvae inside the estuaries during NE monsoon and pre monsoon seasons. The larval movement is corroborated with the tides (Figure 5.6). The simulation indicates that the particle dispersal is clearly supported by the tidal currents (Figures 5.10, 5.11, 5.12). But some unprecedented high quantity of larval abundance is noticed in the field measurement during pre monsoon. Less retention of larvae occured in the Zuari estuary. The particles released from spawning sites moved towards the Mandovi estuary during NE monsoon and pre monsoons.

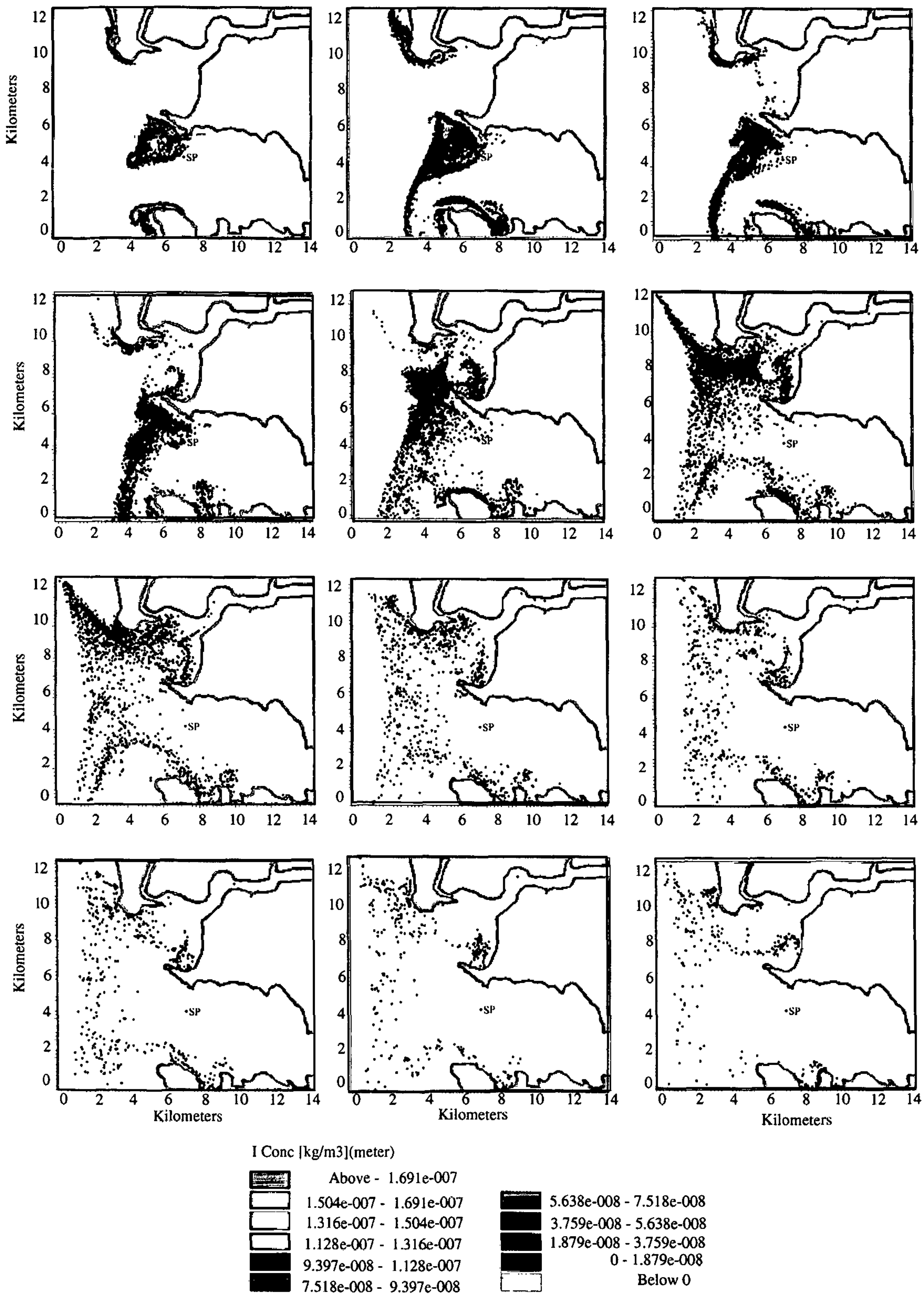
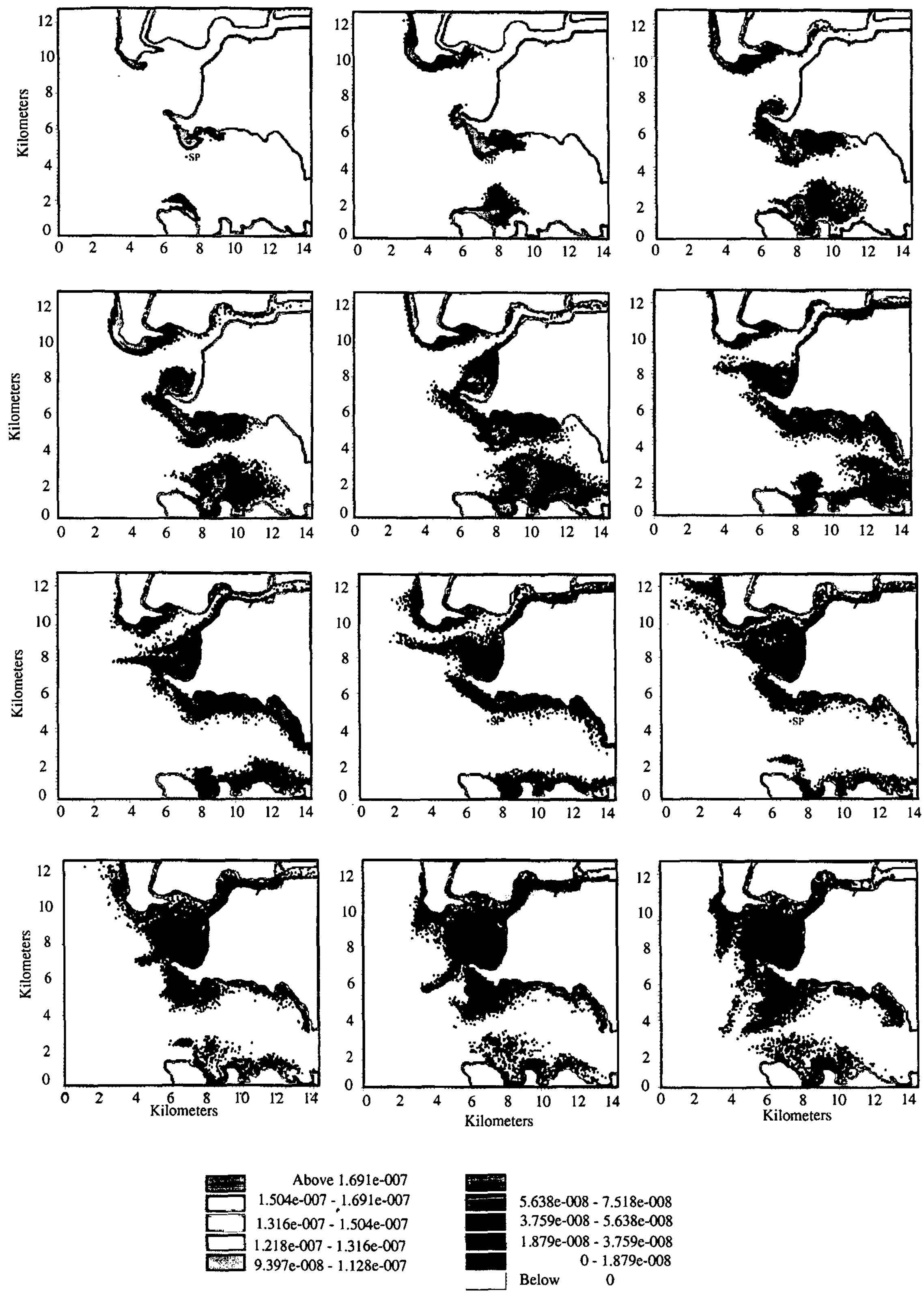


Figure 5.10: Barnacle larval transport during pre monsoon period in Mandovi-Zuari


Kilometers
SP
Above 1.691e-007
1.504e-007 - 1.691e-007
1.316e-007 - 1.504e-007
1.218e-007 - 1.316e-007
9.397e-008 - 1.128e-007
5.638e-008 - 7.518e-008
3.759e-008 - 5.638e-008
1.879e-008 - 3.759e-008
0 - 1.879e-008
Below 0

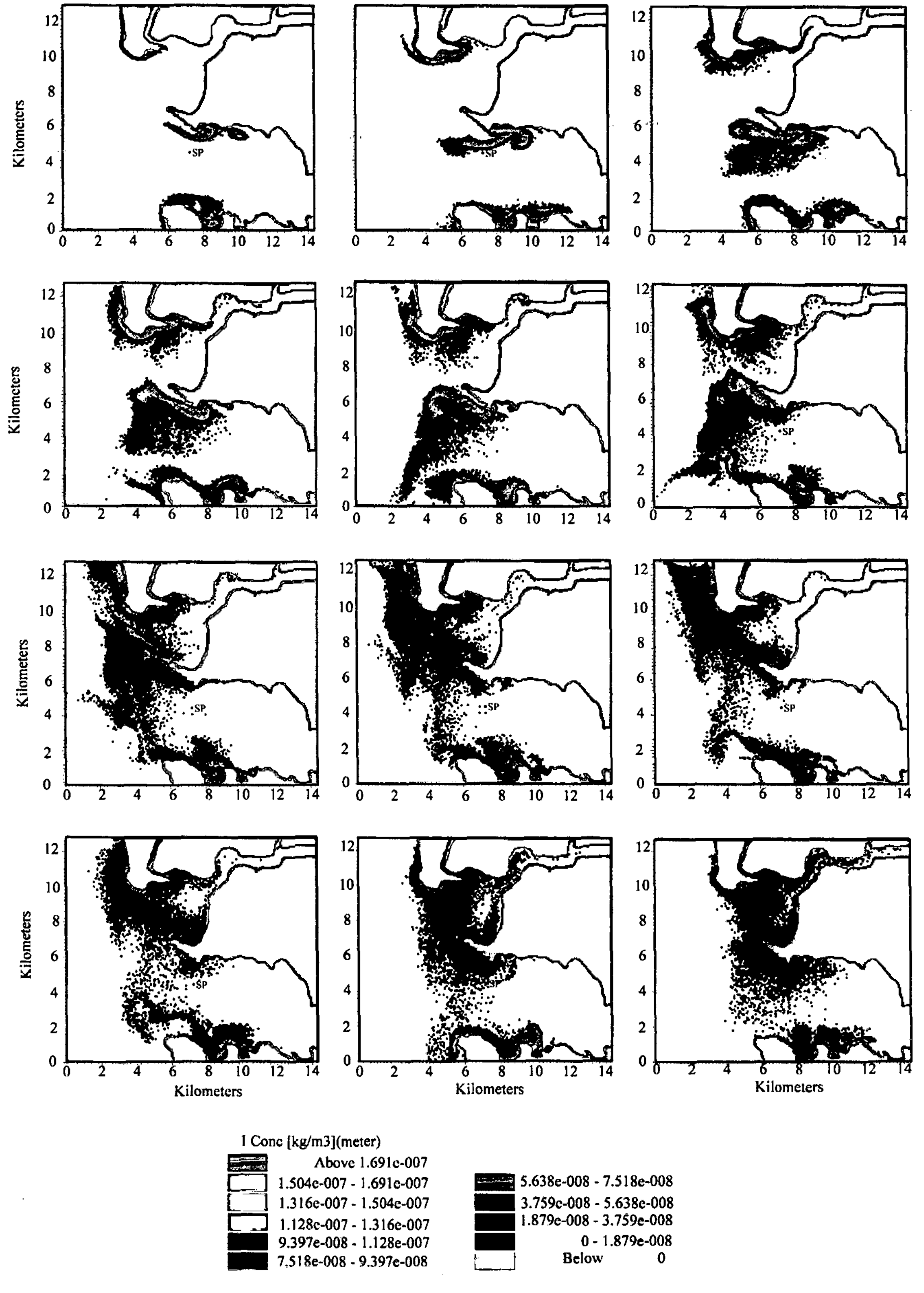


Figure 5.12: Barnacle larval transport during pre monsoon period in Mandovi-Zuari

Barnacles are one of the most charismatic invertebrates of the littoral ecosystems. Species of these groups form large populations of adults in rocky shores and in estuaries that have the capacity to strongly affect the community structure through spatial interference completion [Hughes and Griffiths, 1988; Wootton, 1993; Queiroga et al., 2007]. Recruitment may be broadly defined as the replenishment of a population with new individuals due to the process of reproduction and growth. For marine species with indirect development, recruitment involves several steps: larval development, dispersal during development, supply to appropriate settlement habitats, settlement and juvenile development [Queiroga et al., 2007]. The model results indicates that the presence of barnacle larvae in the estuary is more or less controlled by spawning sites in the outer estuarine areas as there is a clear presence of larvae coming from other sites and settling in the estuary. But, the sites contributing to this abundance vary seasonally.

The model results (Figure 5.13) for December, May and October are consistent with the field observations (Figure 5.6), but October month showed unprecedently high observed values. The quantum of larvae reaching the estuary on the sampling dates (Figure 5.13) indicates that the seasonal spawning sites are relevant in the abundance of barnacle larvae at the sampling point. The larval population in the estuary is well-mixed and the geographical barriers are playing only a very limited role in their retention; hydrodynamics being the major driving force into their transport.

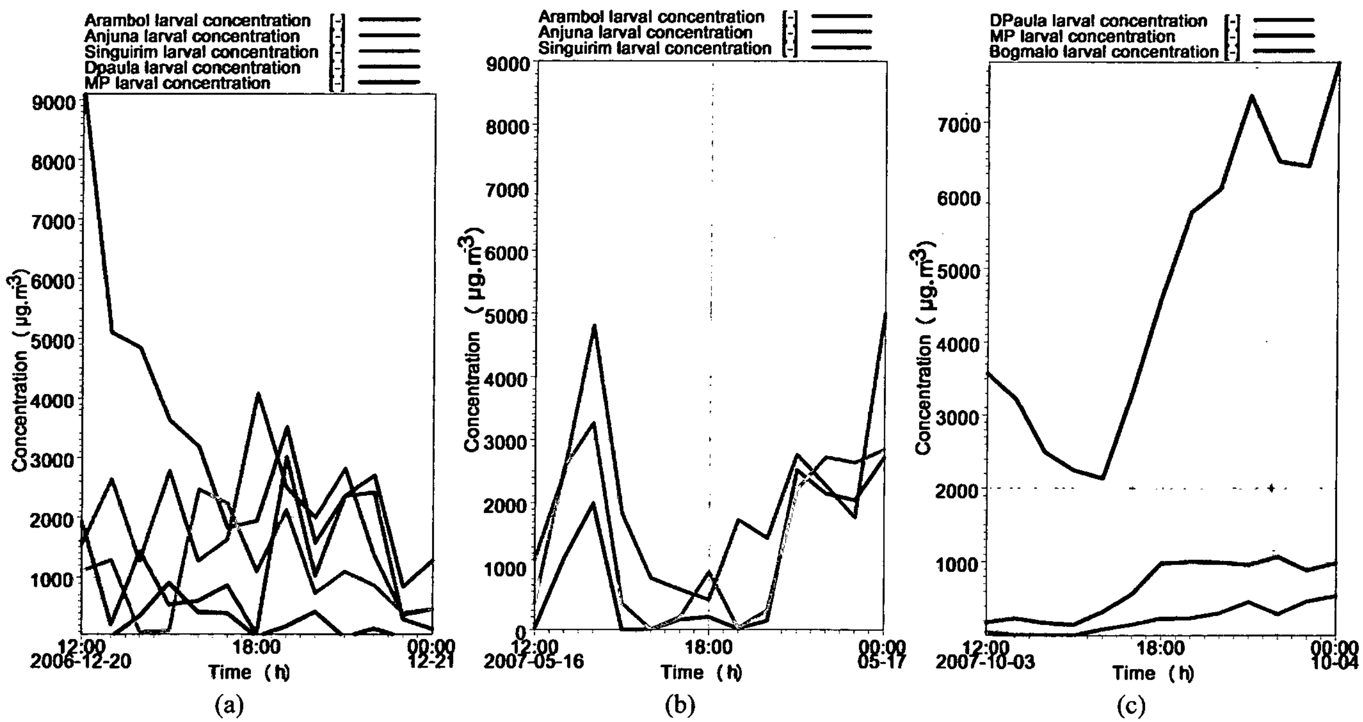


Figure 5.13: Quantum of larvae reaching the sampling point inside the estuary from major spawning sites during (a) December, (b) May (c) October

It is likely that the spawning sites may vary remarkably from the modelled sites. Any stony substratum inhabiting barnacles may also form source of the larvae. It may be noted that a study carried out in the laboratory showed the minimum age of barnacles to release larvae as 28 days [Desai et al., 2006]. The active reproduction in barnacles span over the entire year, with a lull during monsoon. This was observed in a dominant barnacle *Balanus amphitrite* inhabiting the spawning areas [Desai and Anil, 2005]. However, there is no distinct pattern of spawning over an annual cycle. Maximum percentage of barnacles, *Balanus amphitrite* with ripe ovaries was observed during pre monsoon and early pre monsoon months [Desai et al., 2006] indicating higher density of these nauplii during these seasons. October being a month supported by spawning sites from south, the flow apparently supports the larval release from Dona Paula for the months of December and May.

The relatively higher abundance of barnacle larvae in October (Figure 5.6) can also be attributed to other factors such as rainfall, location of spawning and stock abundance, which are not considered in the present study. Unprecedented precipitation followed by a sunny day, and spawning from a site other than the rocky shore like a cement pillar or anchored vessel may give rise to erroneous comparison. This indicates the relevance of repeated time-series sampling to confirm the larval transport process. The physical observations in the study region during October indicate favourable wind and current patterns corroborating the view that more barnacle larvae are transported to the estuary from the southern sites (Figure 5.14). Turbulent tidal flow forces the larvae to undergo mortality, however this depends upon the type of larvae. Barnacle nauplii and cyprids have no effect on turbulent tidal flow compared to larval forms of mollusks (veligers) [Jessopp, 2007].

Naupliar development occurs in pelagic surface to subsurface waters of the shelf, and mostly consists of naupliar and cyprid stages. The release of larvae mostly coincides with high tide, and newly released nauplii and subsequent stages depend on flow of water (Figure 5.6). The modelled and observed pattern of larval dispersion along the coast is similar in December and May. Qualitatively we are able to interpret their abundance in a region, based on their dispersion characteristics. Larvae are accumulated in the spawning

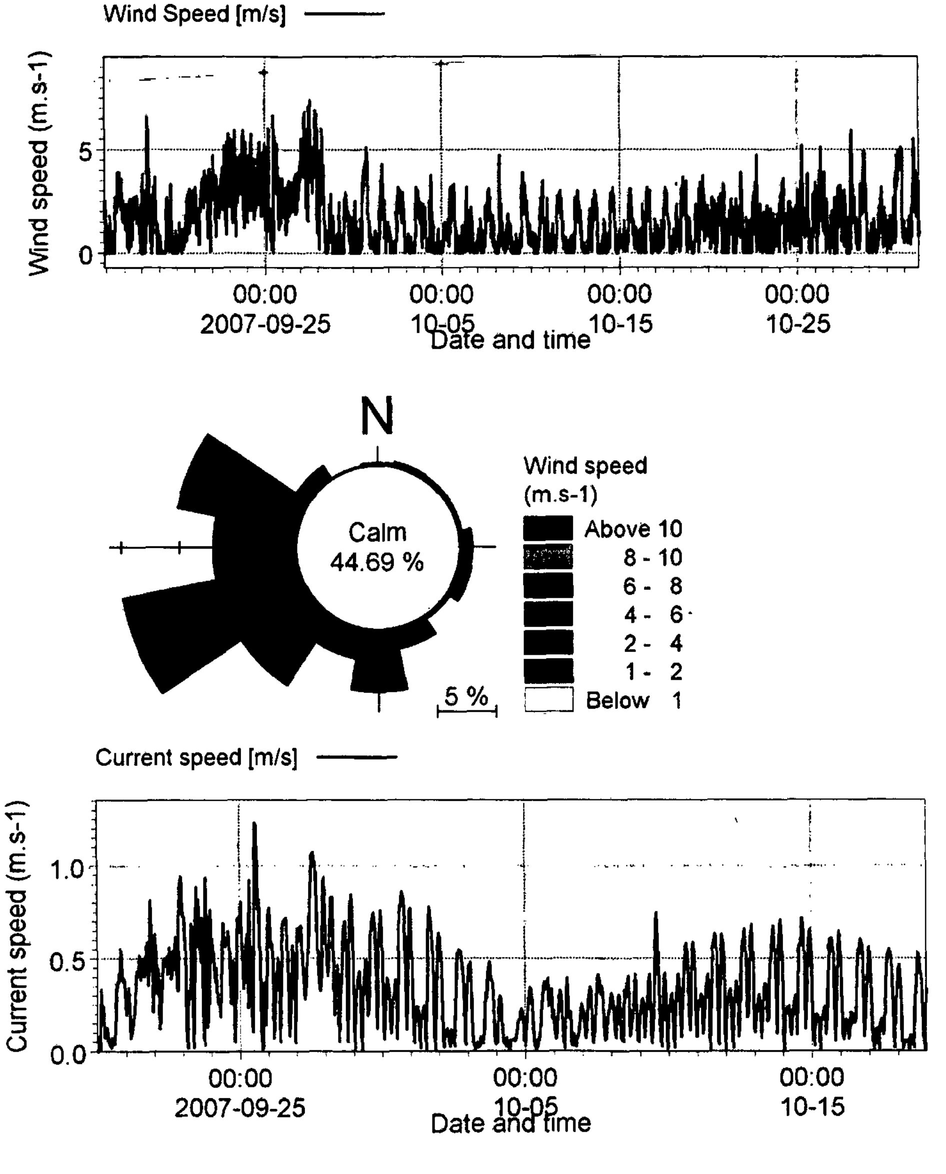


Figure 5.14: Prominent wind and current direction during the unprecedented larval abundance during pre monsoon

site near Dona Paula during October (Figure 5.6). The abundance is comparatively less in May than December with a wider dispersal pattern. In October, a sampling away from the dispersal core reflects a lesser abundance as the larvae may not be spreading to this point. The dispersal core or spawning site is very relevant in this month as dispersal zone is narrow. Therefore, a slight change in the spawning site will reflect a major change in the larval availability at a particular point. The simulated tide and current (Table 4.2) explains the possible transport of larvae along with changing hydrodynamics. Tidal fronts which have been correlated to larval accumulation occur in shallow and not in deep waters [Epifanio, 1988; Clancy and Epifanio, 1989]. It can be pointed out that larval return to open-coast habitat can potentially occur passively by eddy diffusion from an offshore larval pool to shallow water, semi-continuous advection and advective transporting events which may involve vertical swimming behavior, while active transport can potentially be achieved through swimming shore-ward [Pineda, 2000].

Larval abundance in the estuary significantly increases with tide amplitude as flood currents push more larvae to the estuary. Compared to larvae of organisms living in the open coast, estuarine organisms still have to solve an extra problem after having been transported to the near shore environment, that is finding out estuarine inlets and travel stream. The currently accepted view is that invertebrate and fish larvae migrate into estuaries using selective tidal stream transport [Forward-Jr and Tankersley, 2001]. During upstream selective tidal stream transport, larvae settle on or move close to the bottom during ebb tide to avoid being displaced seaward or ascend in the water column during flood tide [Queiroga et al., 2007].

An offshore sampling of barnacle larvae outside the estuarine domain clearly indicated a less abundance of larvae. The average abundance of larvae which was collected from offshore domain during 3 different sampling periods was 474 ($\pm$664) larvae per 100 m^3, which is much lower than the larval abundance within the estuary. Alvarez et al. [1990] illustrated through their study that along-shore diffusion was on an average ten times stronger than the cross-shore diffusion. This corroborates our numerical experiments that the larval spread is only in the coastal and estuarine waters unlike a pelagic offshore larval pool in the case of Californian barnacle [Pineda, 2000]. Non-decapods marine invertebrate larvae are generally small and have limited swimming ability [Chia et al., 1984], and therefore those larvae must probably be transported back by diffusion or advection [A.Okubo, 1994]. It is also suggested that swimming is unimportant for most of the marine invertebrate species [Shanks, 1995], although it is a possibility for certain larger decapods larvae and other large short lives larvae [Olson, 1985; Pineda, 2000].

5.4 Aggregation pattern of fish larvae an open coastal stretch: off Mangalore

5.4.1 Background

Fish landing data shows that Mangalore contributes to about 40% of the total fish landing of Dakshina Kannada District. In the coastal villages, about 75% of population is engaged in fishing related activities. Fishing operations are carried out using purse-seines, otter trawls, and long-lines with mechanised boats, whereas non-mechanised boats are used for gill netting or cast nets and other small scale fishing activities.

Experimental trawling undertaken in the study area have shown that the area is dominated by a variety of economically important finfish and shellfishes such as portunid crabs, flat fish, squids *Loligo* sp., peraeid prawns, pomfrets sciaenids etc. These observations clearly indicate that the fisheries play an important role in the economy of this region. Being an industrial area, the spawning, migration and breeding activities of the fishes are widely affected in the Mangalore coastal region. For this purpose, it is necessary to have baseline information on the occurrence of fish eggs and larvae and spawning activities of the fishes.

5.4.2 Spawning behaviour of fish/shellfish larvae in the Mangalore coastal region

1. Shell fishes in the vertical haul: Vertical distribution data of decapod larvae off Mangalore showed that the *Lucifer* sp. dominated in the study area. It was well rep-

resented throughout the study area with density ranging between 435 and 6958 per 100 m^3. Larval stages of *Acetes* sp., occurred during all sampling occasions and its abundance ranged from 435 to 4784 per 100 m^3. Penaeid larvae were represented by commercially important prawns such as *Metapenaeus dobsoni*, *Metapenaeus affinis* and *Penaeus merguiensis*. Among *carideans*, only larval stage of *Palaemon* sp. was represented in this area. *Callianassid* larvae were not common. The brachyuran zoea were not well represented except during March and April. The groups that occurred in vertical hauls were encountered in horizontal and oblique hauls. Larval stages of *Lucifer* sp. dominated. *Acetes* sp. was relatively uncommon. Penaeid larvae were represented by the same species collected in vertical hauls, but their density was relatively lower. Carideans were represented by larval stages of *Alpheus* sp. as against a sample representation of *Palaemon* sp., Brachyuran zoea in both hauls were also collected in a few samples in small numbers, while porcellinid zoea was collected in oblique hauls.

The compilation of data [Verlecar et al., 1998] and previous records [Rivonker et al., 1990] clearly indicate an average abundance of peanaeid shrimps in the water column. This indicate the relevance of taking up fish eggs and larval abundance studies in the region.

2. Fish eggs and larvae: The collection of fish eggs and larvae were carried out along with zooplankton samples. In the vertical haul, fish eggs and larvae ranged from 0 to 4711 and 0 to 236 per 100 m^3. The fish eggs and larvae occurred in large numbers during September and November, 1997 and February, 1998 while fish larvae were mainly observed in September and October, 1997 and March, 1998. In the horizontal hauls, fish eggs and larvae were poorly represented while in oblique hauls, fairly good numbers comparable to vertical hauls were recorded. Sufficiently large number of fish eggs and larvae were observed in October 1998 in oblique hauls while fish larvae were almost absent during this month. Comparison of fish eggs and larvae in different periods showed that fish eggs and larvae are present throughout the study period [Verlecar et al., 1998], but their numbers vary depending on the season. Monthly values showed that decapod larvae were much higher than the

fish eggs and larvae at both locations. Fish eggs and larvae and decapod larvae in combination form a maximum of 4% of the total zooplankton abundance off Mangalore. The percentage composition of fish egg, larvae and decapod larvae does not show significant differences ($p > 0.05, ANOVA$). These observations indicate that Mangalore region can be a prospective fishing ground, irrespective of the season, but can be a prospective nursery ground too.

3. Spawning season: One of the remarkable characteristics of fishes is that they have high fecundity. However, the survival of fish eggs, fish larvae and decapod larvae depends on the predators and the surrounding environment. The eggs of majority of bony fishes are of same size, planktonic in form and hatch into larvae of about 3 to 6 mm in length. The larvae are transparent, with prominent dark eyes, large yolk and they swim by wriggling movements throughout the water column. Because of this behaviour, large differences were observed in number of fish eggs and larvae in different hauls while their numbers were almost steady in vertical hauls. Feeding by these larvae takes place during dusk and dawn. Their first food is often large algal cells but they also rely on copepod nauplii or larval stages of molluscs. During the end of larval life as zooplankton, metamorphosis takes place making the larvae transparent, fins and scales develop and they change their shape into that of little fishes. When fish metamorphosise they are ready to settle in a nursery ground, usually along the coast or estuary. The migration from spawning ground to nursery is called the larval drift. So, irrespective of the season a larval drift study in the Mangalore region will improve the understanding of the prospective nursery areas for Mangalore region.

5.4.3 Effect of physical process and biological abundance on fish larval transport in the Mangalore coastal region

Particle trajectories for different spawning sites have been simulated as field studies are not revealing any clear pattern of abundance of egg/ larvae along the coastal waters off Mangalore. The field observations indicated that the larval abundance is high without any specific spatial variation. The particle trajectory plot was employed to see the possible dispersal of larvae from different coastal locations to understand the possible mechanisms influencing larval dispersion in the region. The larval tracks are having a uniform pattern except for their dispersal at the south boundary of the Mangalore domain (Figure 5.15). This is in concurrence with earlier field studies [Rivonker et al., 1990] which have shown that the fishing grounds are spread over the region without any spatial changes seasonally. Like zooplankton, initially larvae live as plankton (drifting in water) and they make daily

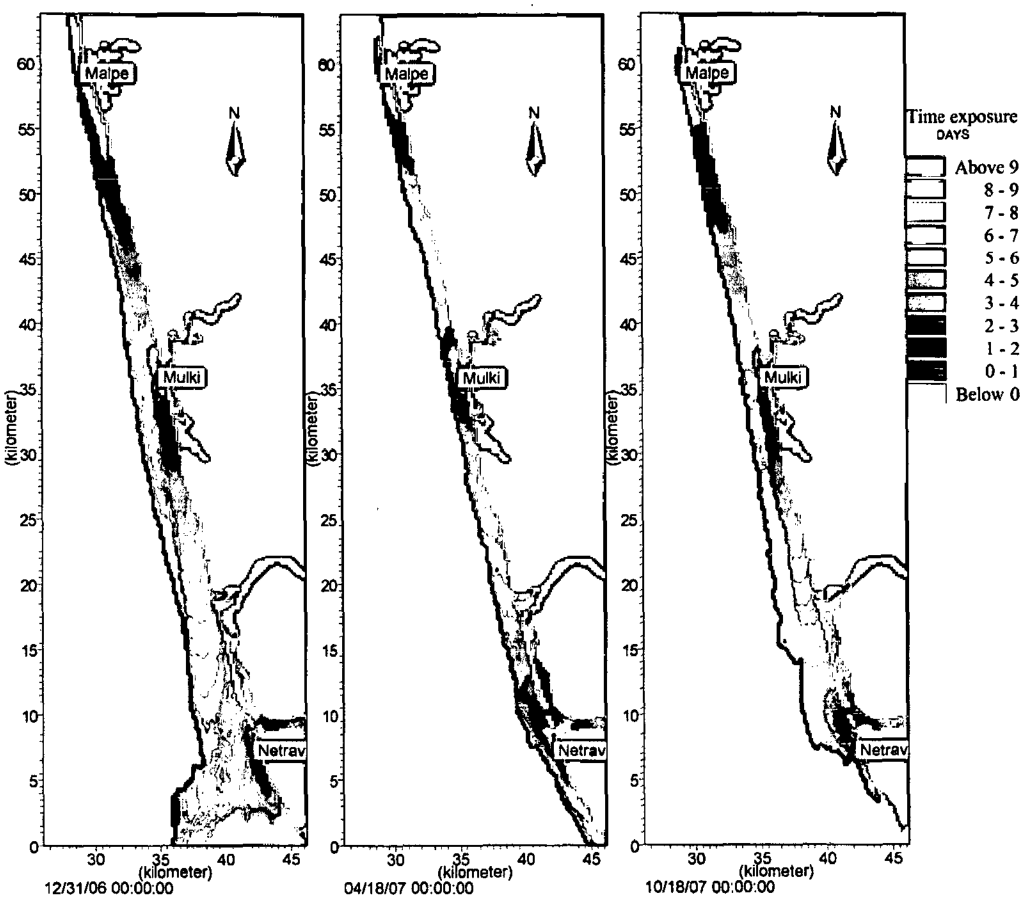


Figure 5.15: Simulation of particle trajectories from three stations along the coastal waters of Mangalore during pre monsoon, post monsoon and NE monsoon

vertical migrations from below the euphotic layer towards the surface. After attaining certain growth, fishes tend to move off slowly into somewhat deeper waters and thus movement has been described as a horizontal diffusion away from the shore. During this period of their life cycle, they feed on local foods such as copepods, bivalves and worms. Their speed into deeper waters gradually leads them to grounds where adults live and gradually they are recruited to adult stocks. Length-weight analysis, maturity and spawning behaviour showed that the fishes off Mangalore belong to one year or less than one year year-class [Rivonker et al., 1990]. Most of the fishes were immature, and sex could not be identified. Commercial fish species during their adult life, mostly migrate every year from feeding grounds to spawning grounds and back again. The spawning season may last for few days or few months for particular species. The eggs take up water as they are released and spawn in batches. During this study period [Verlecar et al., 1998], not a single fish having mature ovary was detected. It can be stated that spawning takes place in offshore waters and the eggs as well as larvae could get drifted away by tides and currents to the coast where the eggs hatch out into larvae and mature into young fish. Thus, Mangalore coast having rich phytoplankton and zooplankton biomass could act as a good nursery ground for the commercially important fishes as evident from the predominant zero-year (*i.e.* ≤ 1 year) size-class of the fishes, fish egg and larval distribution.

Chapter 6

Summary and conclusions

6.1 Summary

Indian coastal waters are rich in marine organisms and proper protection of their larval population are important for sustaining these organisms. But, there are certain marine organisms which are harmful and needs to be controlled. A proper demarcation of ideal sites of spawning and larval transport will help in managing the larval population. Management measures like closed area and season for the fishery will be more effective with the help of a decision support system. Numerical simulations provide a quality data base which can supplement the decision support system. The present study is an attempt in this direction and probably for the first time such study is conducted for the coastal waters of India. The broad objectives of this study are as follows:

(i) to find out the influence of environmental parameters on the biology of the given ecosystem

(ii) to track larval transport and biological abundance in relation to environmental variables

(iii) to compare biological abundance and fish larval transport in three different marine ecosystems, namely, the GoK (a semi-enclosed basin), Mandovi-Zuari (estuarine system of Goa), and Mangalore coastal region (an open coast with seasonal influences)

The initiatives taken for fulfilling the objectives include the following investigations:

(i) analysis of satellite chlorophyll data along the southwest coastal waters of India to derive a biological calender for sardine

(ii) tracking the larval survival and establish a link between food and sardine inter-annual variability

(iii) generating the hydrodynamic pattern of three marine ecosystems selected for the study

(iv) identifying specific spawning locations and biology of the organisms considered in the respective regions

(v) numerically tracking the transport of larvae released from spawning sites based on hydrodynamics of the regions, and comparison with measurements

(vi) interpreting the data sets generated by numerical simulation studies to infer the nursery areas and seasonal importance of the larvae of marine organisms in three diffrent marine ecosystems and

(vii) identifying the lacunae in the study for calling upon future investigations

The tracking of sardine along the southwest coast of India is an attempt using satellite derived chlorophyll data to explain the larval survival and inter-annual variability from a synoptic scale of view [Grinson George et al., 2011]. Active breeding period in the annual biological calender of sardine corresponds to the months with higher chlorophyll in ambient waters. Chlorophyll biomass during bloom initiation month can be a precursor to the sardine biomass for the year. But, lack of continuous larval data sets on sardine larval abundance is a major lacuna in developing a model for prediction of sardine biomass along the southwest coast of India.

Further, efforts are taken to illustrate the significance of using the physical factors like wind, tides, current speed and ocean colour in defining fish and shell fish larval transport. Numerical modelling is used for explaining the bio-physical link involved in fish and shell fish larval transport in the coastal waters. They also corraborate the earlier suggestions on larval abundance, but explain further the bio-physical mechanisms controlling the larval abundance in a synoptic scale.

Variation in sardine abundance could be attributed to variability in the physical parameters such as upwelling, Mean Sea Level (MSL), temperature, wind stress, rainfall and monsoon conditions [Longhurst and Wooster, 1990; Krishnakumar and Bhat, 2008]. However, such indicators are not a direct trophic link to sardines. The important factors responsible for the offshore-inshore migration appear to be the strength and duration in the upwelling bloom which brings about variations in physicochemical and biological properties of the coastal waters. But, a phase lag between upwelling and intense production has been reported in earlier studies in this region [Kumar et al., 2008]. Hence, chlorophyll concentration in coastal waters is the most important factor for establishing a trophic link that summarizes the above physical and chemical processes. An early spawning and a time lag in the development of food (through a break in monsoon or upwelling) would be detrimental to sardine recruitment. Consequently, chlorophyll concentration during the bloom initiation month substantially explains the interannual variability in sardine landings. The spatial and temporal variations in the intensity of chlorophyll in the coastal waters is proportionally reflected in the sardine abundance of the respective area.

Biological data sets from various sources and numerical simulation of particle tracking helped in identifying the major spawning sites of fishes in the GoK. Fish larval transport studies in the GoK shows that particle transport modelling can be an effective tool and decision support system in identifying the locations that are potential nursery areas for fish larvae. Management measures like demarcation of closed areas and closed seasons can be implemented in the GoK based on this tool. The spawning sites may vary with seasons, but the dispersal of larvae ensures that larvae reach nursery grounds in the GoK rather than getting dispersed in the gulf mouth. The fish larval abundance or aggregation during different seasons suggests the priority areas of likelihood of larval retention. Presently, regulations are enforced only in the Marine National Park and Marine Sanctuary areas in the southern gulf, which is also an area of maximum particle retention, as seen in the modelling studies. Thus, the model demonstrates quantitatively a definite pattern on redistribution of fish larvae in the southern gulf, leading to more abundant fish populations. Hitherto, a significant percentage of particles $\geq$30% are retained at two other locations *viz.*, areas beyond the three eddies inside the gulf and upper north-western boundary of the gulf which are not regulated for fishing. This stipulates the necessity of enforcement of fishing regulations in these areas during pre-monsoon and southwest monsoon seasons (Figure 5.2) for ensuring sustained fishery in the region.

Mangalore fishing ground is also rich in fish. The aggregation of fish larvae in the fishing ground is due to the prevailing currents in the Mangalore region. The sampling experiments conducted earlier [Rivonker et al., 1990] indicate the abundance of rich fishery, and the numerical simulations also substantiate this finding. The temporal variation in fish and their biological cycle may be attributed to the seasonal changes. Upwelling plays a major role in deciding the biology, as we have discussed in the case of Indain oil sardine (Chapter 3), which is evident from the larval samplings along the Mangalore coast. But, eggs and larvae are present throughout the year with varying abundance which is also commom for a diverse tropical fishery existing here. Therefore, the drift and aggregation of larvae from offshore and north boundaries of the Mangalore domain is likely to increase fish abundance in the Mangalore region as evident from the numerical simulations.

The importance of barnacle larval transport study is to identify the seasons and spawning sites of bioinvasive barnacles in the coastal waters of Goa. Surveys indicated a similar abundance pattern which was not shown by the models. The barnacle population abundance is contributed by spawning sites outside the estuary and the sites contributing to the barnacle larval abundance varies from season to season. Spawning sites found on the north of the estuary is significant during all seasons, except post-monsoon. The barnacle larval population in the estuary is well mixed. The spawning sites from north and south of the estuary are contributing to the larval abundance. Larvae traverse as far as 78 km along the coastal waters with a minimum dispersal of 3 to 5 km. Barnacle larval abundance is higher during post-monsoon season as large quantities of larvae are supplied from spawning sites located south of the estuary. This is further strengthened by the wind pattern during the season. Unlike a pelagic open offshore larval pool for barnacles in Californian coast [Pineda, 2000], the acorn barnacle larvae in the Mandovi-Zuari estuarine system is concentrated only in the nearshore waters and estuarine mouth as seen in the observations and numerical experiments. Larval abundance in the estuary significantly increases with the tidal amplitudes as larvae are pushed into the estuary during the flood currents.

6.2 Importance of the study and future perspective

Analysis of remotely sensed chlorophyll data provided a putative trophic link for explaining variation in sardine catches along the waters of the southwest coast of India. However, this information has to be coupled with other appropriate biological data for forecasting fish distribution. Thus, satellite chlorophyll alone in its present state cannot be an alternative to *in situ* chlorophyll. The absolute chlorophyll present in *Case-2* waters often gets challenged by the turbidity contributed by other optical constituents. It is the judicious application of both satellite and observed data that will help in deducing the correct picture. There are many developments in the building of trophic models of aquatic ecosystems [Hall and Mainprize, 2004]. There is potential for phytoplankton data to serve in future as a surrogate for sardine biomass. Usually, investigations in fisheries biology lack time series environmental or other biological data sets [Longhurst and Wooster, 1990; Madhupratap et al., 1994]. The combination of satellite data sets with fisheries data can lead to robust conclusions. Time series data for a long period will be required to confirm and determine the large-scale fluctuations in abundance, population crashes and subsequent revival of this major pelagic fishery in the southwest coast of India.

Numerical simulation is an attempt to supplement the existing decision support systems to enable the right demarcation of nursery areas for fishes. Similarly, the technique can be extended to identify the potential spread of bio-invasive obnoxious species like barnacle thus helping in deciding the place of ballast water release and infrastruture development and related activities. The biological relevance of numerical modelling and remote-sensing is restricted to few operational activites in fisheries. Potential fishing zone advisory is the major activity of this kind in India. The findings of this thesis signifies the usage of numerical modelling and remote-sensing in fisheries management. Aggregation pattern of fish larvae and an estuarine larval pool for barnacles may be seen as a manifestation of physical processes which could supplement the other ongoing biological investigations. There are numerous possibilities of improving the model by addition of biological features like predation, mortality and behaviour. The present study invokes the idea that the demarcation of marine protected areas should be based on the rationale that areas of maximum likelihood of retention of icthyoplankton will be a better fisheries management strategy, imbibing the concepts of an ecosystem-based spatially structured approach. Being a complex study involving a lot of uncertainities, the role of coastal processes in fish and shell fish production and dynamics deserves further investigation with a better time series sampling of early life stages in marine organisms.

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Appendix A

Abbreviations

- RS-GIS - Remote Sensing and Geographical Information System
- NE - North East
- SW - South West
- WCI - West Coast of India
- PLD - Pelagic Larval Duration
- SeaWiFS - Sea-viewing Wide Field of view Sensor
- NASA - National Aeronautics and Space Administration
- WLR - Water Level Recorder
- AWS - Autonomous Weather Station
- RCM - Recording Current Meter
- ICMAM - Integrated Coastal and Marine Area Management
- COP - Captain of Ports
- HT - Heron Tranter
- HD - Hydrodynamics
- DHI - Danish Hydraulic Institute
- ADI - Alternating Direction Implicit
- DS - Double Sweep
- UTM - Universal Transverse Mercator

- CFL - Courant-Friedrichs-Lewy
- WNW - West North West
- SSW - South South West
- NNE - North North East
- PA - Particle Analysis
- ICES - International Council for the Exploration of the Sea
- SST - Sea Surface Temperature
- MSL - Mean Sea Level
- NHO - Naval Hydrographic Office
- RMS - Root Mean Square
- ENE - East North East
- WSE - West South East

Appendix B

List of manuscripts accepted/ under revision from the thesis

1. **Grinson George**, B. Meenakumari, M. Raman, S. Kumar, P. Vethamony, M. T. Babu, and X. Verlecar. Remotely sensed chlorophyll: A putative trophic link for explaining variability in Indian oil sardine stocks. *Journal of Coastal Research*, DOI:10.2112/JCOASTRES-D-10-00070, 2011. *In Press*

2. **Grinson George**, Ponnumony Vethamony, Kotteppad Sudheesh, Madavana Thomas Babu., 2011. Fish larval transport in a macro-tidal regime: Gulf of Kachchh, west coast of India. *Fisheries Research.* 110 : 160–169.

3. Chetan A. Gaonkar, Samiksha S. V., **Grinson George**, Aboobacker V. M., P. Vethamony and Arga Chandrashekar Anil. Numerical simulations of barnacle larval dispersion coupled with field observations on larval abundance, settlement and recruitment in a tropical monsoon influenced coastal marine environment. *Journal of Marine Systems. Accepted with minor revisions.*

4. **Grinson George**, D. V. Dattesh, Chetan A. Gaonkar, V. M. Aboobacker, P. Vethamony, and A. C. Anil. Barnacle larval transport in the Mandovi-Zuari estuarine system, central west coast of India: field measurements and numerical experiments. *Under review.*

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Remotely Sensed Chlorophyll: A Putative Trophic Link for Explaining Variability in Indian Oil Sardine Stocks

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ABSTRACT

GEORGE, G.; MEENAKUMARI, B.; RAMAN, M.; KUMAR, S.; VETHAMONY, P.; BABU, M.T., and VERLECAR, X. 2011. Remotely sensed chlorophyll: a putative trophic link for explaining variability in Indian oil sardine stocks. *Journal of Coastal Research*, 00(0), 000–000. West Palm Beach (Florida), ISSN 0749-0208.

The landing of Indian oil sardines, *Sardinella longiceps* Valenciennes, 1847, along the southwest coast of India is highly variable. A few physical parameters and processes correlated with sardine landing could not establish a flawless connection and explain the phenomena of interannual variability. Earlier research has indicated that the probable appearance and disappearance of sardines is an active movement in search of food and favourable conditions. But no specific study has been carried out to explain the variability of sardine catch based on chlorophyll availability on a synoptic scale. An attempt is made in this study to correlate variability in chlorophyll *a* with sardine landings along the waters of the southwest coast of India. We have estimated monthly averaged surface phytoplankton biomass along the waters of the southwest coast of India from the shoreline up to the 200-m isobath for 10 years from *SeaWiFS* ocean-colour data. This estimation is compared with the biological calendar of Indian oil sardines. The average chlorophyll *a* for the bloom initiation month (1998–2006) matches very well with oil sardine landings. The results imply that the concentration of chlorophyll during the bloom initiation month can be used to assess the quantity of fish that recruit into the population. Finer scale spatial variations in the chlorophyll along the coastal waters help in deciphering the migratory pattern of sardines during their active breeding phase. This study shows that 39% of interannual variability in fish landings is related to availability of chlorophyll *a* during the bloom initiation month.

ADDITIONAL INDEX WORDS: *Upwelling, fisheries, ocean colour, phytoplankton, southwest coast of India.*

INTRODUCTION

1 The interannual variability in the landings of Indian oil sardines, *Sardinella longiceps* Valenciennes, 1847 (hereafter called sardines), has been explained as an outcome of seasonal variability in the marine environment (Hornell, 1910a). Based on the physical parameters and processes such as sea surface temperature, rainfall, sea level, and upwelling, indices relating to total sardine catch with environmental factors are formulated (Longhurst and Wooster, 1990). These indices, formulated based on a correlation between sardine catch and rainfall, wind stress, and sea level, failed with time as a result of large variability in landings and correlated factors (Madhupratap, Shetye, and Nair, 1994). Failed correlations should not be dismissed summarily on the assumption that data were faulty, the criteria for comparison were ill founded, or the relation spurious; rather, the cause and effect should be explored in detail to explain the phenomena (Skud, 1983). There are several interrelated factors that are responsible for the recruitment of fishes and their abundance. The estimation of all environmental variables responsible for this is perhaps a difficult task. Surplus models, recruitment models, and similar time series models globally were having limited success. Changes in physical factors affecting marine food-web based studies gained more relevance because of this. The concept of fish stock assessment rather concentrates now on predicting the expectant biomass based on ambient environment changes that have a trophic link (ICES, 2000; NRC, 1999).

Biological studies suggest an extended spawning period from May to September for sardines (Antony Raja, 1969; Hornell, 1910a; Hornell and Nayadu, 1924; Prabhu and Dhulked, 1970). After occlusion from the egg, larval development is rapid in sardines, with yolk sac absorption taking place in 3 days (Nair, 1960). These larvae will undergo their critical first feeding period almost immediately after yolk absorption (Hunter, 1981; Lasker, 1975; Lasker, 1981). The earliest spawned surviving individuals will be recruited to the fishery by the end of the spawning period, which in turn determines the yearly landings. Thus, larval ecology decides the later abundance of recruits to the fishery. Collating various information cited on young, juvenile, and adult sardines and their feed during spawning period (Devanesan, 1943; Hornell, 1910a; Hornell and Nayadu, 1924; John and Menon, 1942; Van der Lingen, 2002), we can confirm that the larvae are predominantly

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surface and column feeders, with phytoplankton forming a major group, dominated by diatoms like *Fragillaria oceanica*, *Pleurosigma* sp., and *Coscinodiscus* sp. (Kuthalingam, 1960; Nair, 1959).

Sardines feature a fine-meshed filtering apparatus in their gill rakers (Van der Lingen, 2002), with more than 130 gill rakers on the lower part of the gill arch. They are able to filter smaller particles. Therefore, they thrive on very tiny particles that may occur in the coastal waters through which they continually migrate and these tiny particles (phytoplankton), predominated by diatoms occur throughout their range of distribution (Bakun and Broad, 2003). Moreover, sardines are serial batch spawners (as are anchovies, sprats, tunas, *etc.*). They spawn for several days during extended spawning seasons. The fact that sardines employ a combination of migrating capabilities, ability to feed on very small particles, and serial spawning habits, underlines the importance of studying sardines along with their feed availability during the spawning season.

The Hjort-Cushing hypothesis (Cushing, 1974; Cushing 1990; Hjort, 1914) refers to the critical first feeding period and the timing of the spring phytoplankton bloom. In the case of sardine larvae, the bloom that decides its biology is an upwelling-induced bloom, the bloom initiation time and intensity is the only variation that could account for changes in the food supply to sardine larvae. These variations in food supply between different years will be reflected in the larval development and further recruitment of sardines into the fishery. This aspect was not examined in the earlier studies on sardine landing variability.

Sardines perform a normal migration from offshore to coastal waters and *vice versa* coinciding with the customary wind conditions (Hornell, 1910b). A gradual increase in temperature within the range of 26 to 28°C is favourable for the inshore migration of the juveniles, and with increasing temperatures (above 29°C) during March to May they disappear to deeper waters (Chidambaram, 1950). The specific gravity of water, which is above 1.023 during March to May, also promotes the disappearance of the shoals. The shoreward migration of spawners during monsoon months and their outward migration to deeper waters during postmonsoon months is for feeding (Nair 1959) on the luxuriant growth of phytoplankton that blooms up during the onset of monsoon (Chidambaram, 1950; Hornell, 1910b; Hornell and Nayudu, 1924; Nair, 1953). The longitudinal migration either way is an excursion from offshore to inshore waters and *vice versa* due to availability of food and favourable hydrographic conditions (Devanesan, 1943).

The shoals start disappearing from the northern region first, and then from the southern Malabar area. From April to September, the shoals of spawners and juveniles migrate from offshore to inshore all along the west coast following the onset of bloom (Antony Raja, 1972). This observation suggests a northward migration of sardines steadily during southwest monsoon period and retrogression from north to south in the northeast monsoon phase (Figure 1). Lack of continuous seasonal information to characterize synoptic scale variability in chlorophyll concentration of the region was an impediment to verifying the food availability between different years to explain the interannual variability in sardine landings. Also, it was not feasible to study the spatial and temporal variations in chlorophyll concentration in these areas because of nonavailability of *in situ* data. With the advent of remote sensing, however, this was possible with ocean-colour data. Platt, Yaco, and Frank (2003) applied remotely sensed ocean-colour data as direct evidence for a putative trophic link and suggested it as an important link in future analyses of dwindling fish stocks. Time series phytoplankton cycle information derived from satellite data can be used to construct a variety of ecological indicators of the pelagic system useful in ecosystem-based management (Platt *et al.*, 2009).

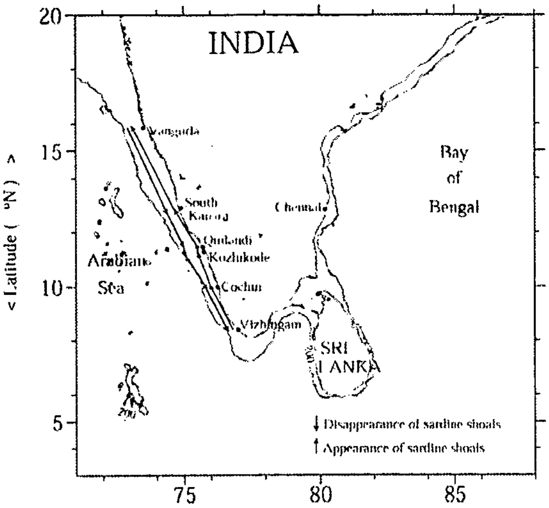

Figure 1. Schematic representation of progression of sardine shoals from Vizhingam to Vangurla (Chidambaram, 1950; Hornell, 1910b) and their departure in the reverse direction (Panikkar, 1952).

Remotely sensed sea surface temperature (SST) and ocean-colour images reveal eddies and fronts. These features frequently coincide with areas where fish species aggregate as a result of enhanced phytoplankton biomass and primary production, which in turn is linked with changes in nutrient supply or mixed-layer depth. Since higher plant biomass is associated with zooplankton, one might expect to add supplementary information on fish stock distribution from ocean-colour pigment fields. Colour patterns were useful in differentiating the relevance of food over other environmental factors like temperature in fish aggregation, offering better information regarding the location of Albacore tuna (Laurs, Fiedler, and Montgomery, 1984). It was originally assumed that tuna prefer to reside within certain limited temperature ranges, which explains their tendency to aggregate at a temperature front. In instances where colour and SST fronts were spatially separated, they found that tuna actually tend to aggregate on the clear side of a colour front.

Ocean-colour pigments are relevant in detecting a bloom. Fragmented observations in the waters of the southwest coast of India hypothesized two seasonal blooms: (i) upwelling blooms, coinciding with the arrival of prespawning adults

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during May–June, and (ii) winter blooms, in September–October, coinciding with the main fishery for juveniles (Bensam, 1964). For sardines, a filter feeder, the amount of food ingested depends on chlorophyll concentration as well as copepods present in the ambient waters; better availability of food is expected in chlorophyll-rich waters. In the present study, variability in chlorophyll along the waters of the southwest coast of India had been quantified from satellite data and related to annual variability in the sardine landings. The synoptic scale spatial and temporal changes in chlorophyll *a* were useful in explaining the appearance and disappearance of sardine shoals along the coastal waters.

STUDY AREA

The entire sardine fishing ground off the southwest coast of India, extending from 5°N to 15°N, was considered for the study. The seaward limit of the study area extends up to the outward edge of the continental shelf (200-m isobaths) (Figure 2). Figure 1 explains the schematic representation of sardine movement, but the actual dwelling area of sardines is segregated in the satellite image by following the depth contour as shown in Figure 2. The spatial extent of the study area was determined in concurrence with earlier observations (Longhurst and Wooster, 1990). The coastal zone current characteristics and environmental setting described in an earlier study (Dinesh Kumar and Srinivas, 2007) also defines this study area as a narrow continental shelf domain with strong upwelling and downwelling signatures.

METHODS AND MATERIALS

We used data on marine fish landings in India for the period 1985–2006 published by the Central Marine Fisheries Research Institute (Srinath *et al.*, 2006). We collected 316 samples of sardines from the major sardine landing centre at Cochin for length and weight measurements during the study period. Sardine catch is dominated by 0-year class individuals, *viz.*, measuring ≤14 cm total length (Dayaratne and Gjøsaeter, 1986), spawned during the earlier spawning period starting from May (Table 1). The entire breeding activity of sardines is confined to coastal waters with an active artisanal fishery (ring seines, purse seines, and shore seines), which responds with vital fishing efforts depending on fish availability. Mechanized trawlers in the coastal waters are restricted to a period of 45 days starting from 15 June. The artisanal sardine fishery comprised of motorized and nonmotorized country crafts is active during this period also. Decrease in sardine fishery within the study area did not result in heavy landings elsewhere, thus ruling out the possibility of migration of sardines from the study area. Hence, it is assumed that the sardine landings within the study area are representative of stock abundance (Longhurst and Wooster, 1990). This assumption holds good since the present study is restricted to a time period when there was relatively little change in the composition of fishing crafts and gears.

Monthly averaged chlorophyll maps at 9-km spatial resolution derived from *sea-viewing wide field of view sensor* (*SeaWiFS*) satellite data for the period January 1998–December 2006 was downloaded from the website http://oceancolor.gsfc.nasa.gov/cgi/l3 (NASA, 2002). The optically sensitive constituents such as suspended solids and yellow substance in CASE 2 waters in this region (Menon, Lotliker, and Nayak, 2005; Menon *et al.*, 2006) were tackled during extraction of chlorophyll *a* from the composite image using an algorithm for masking turbid waters (Bricaud and Morel, 1987). A trend between sardine landing and chlorophyll *a* during the study period was found using the polynomial trend line, which gave the best fit. Coefficient of determinant was worked out for quantifying the variability in sardine landings and chlorophyll *a* during the bloom initiation month.

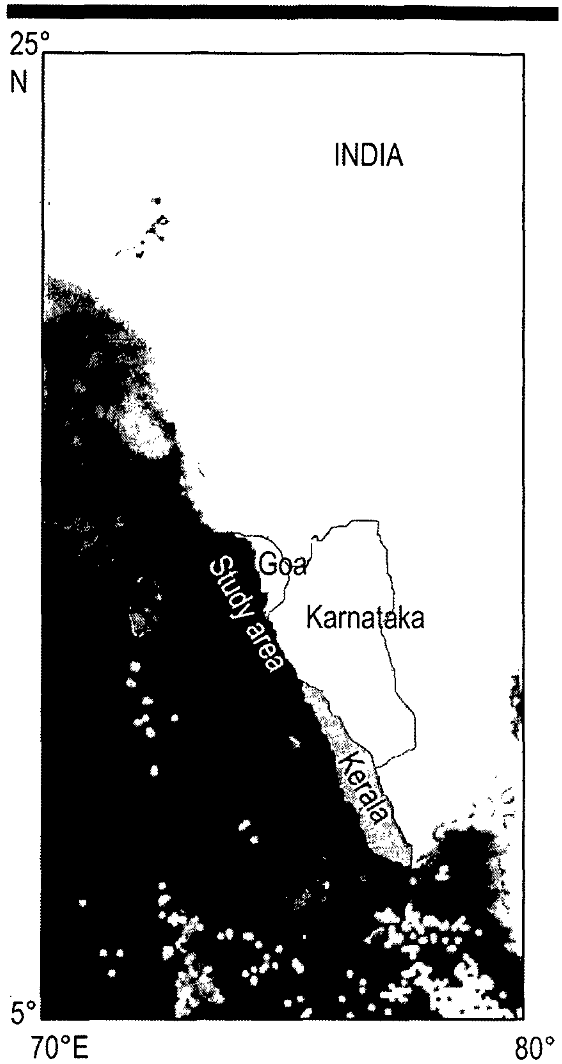

Figure 2. Study area and three major sardine landing maritime states displayed in the satellite image from *SeaWiFS*.

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Table 1. *Average length and weight measurements of 316 random sardine samples from a major landing centre.*

Total Length (cm)	Fork Length (cm)	Std Length (cm)	Gill Girth (cm)	Max Girth (cm)	Mouth Diameter (cm)	Weight (g)
11.64±2.57	10.24±2.28	9.64±2.15	1.77±0.49	1.90±0.52	0.88±0.39	12.58±10.96

RESULTS

The variability in sardine landings, chlorophyll variability, and chlorophyll during upwelling bloom initiation were examined for explaining the interannual sardine variability and sardine migration in the coastal waters.

Sardine Landing Variability

Sardine landing data reveal interannual variability since 1925 with an increasing trend during the study period (Figure 3). Sardine landings showed a drastic decline in 1985 and 1994, which alternated with very high landings of Indian mackerel during these two years. Marine fisheries of the southwest coastal waters are characterized by the predominance of pelagic fish resources dominated by sardines and Indian mackerel (*Rastrelliger kanagurta*), which supports the western Indian Ocean's largest coastal pelagic fishery. Alternating patterns of abundance between these species could have been the reason for these two major falls.

The landing pattern of these two species (Figure 4) along this coast could be compared with the alternating patterns of abundance between sardines and anchovies observed in other upwelling areas of the world. The study period (1998–2006) was a sardine dominant period (period of high sardine and low mackerel). Figure 4 shows a sardine revival phase, and the period reflects an ideal phase for the study of sardines without interference from the mackerel fishery.

Chlorophyll Variability in the Study Area

Observed chlorophyll in the study area during 1984–2006 ranged from 0 to 6.25 mg/m^3 with a mean value of 0.32 mg/m^3 and a standard deviation of 0.59 mg/m^3, indicating that the chlorophyll available in the coastal waters was highly variable. *SeaWiFS* chlorophyll values in the study area remain within the maximum–minimum limits of *in situ* chlorophyll (Figure 5) except for the month of August 2002 (6.557 mg/m^3), which may be due to an unusually high upwelling bloom.

The chlorophyll *a* concentration remained high from May to October, but the peaks varied from year to year. Periods of higher chlorophyll *a* concentration match with the active breeding period of sardines (Figure 6). The biological calendar of sardines (Figure 6) commences with the entry of spawners in May, followed by fresh juveniles during July–August. During September to December, the adults occur in reduced numbers, and the adult population is replaced by large shoals of juveniles. They, however, get numerically reduced in January–February and subsequently disappear, reappearing during May–July. With the onset of premonsoon showers or southwest monsoon rains, they move toward the inshore waters with the gonads in various stages of ripening. The spent and resting adults, on the other hand, appear in small quantities along with their juveniles during January–February, disappear in the following months along with the juveniles, and reenter for their second spawning along with the virgin spawners. For numerically representing the average chlorophyll, which determines the active breeding phase, chlorophyll

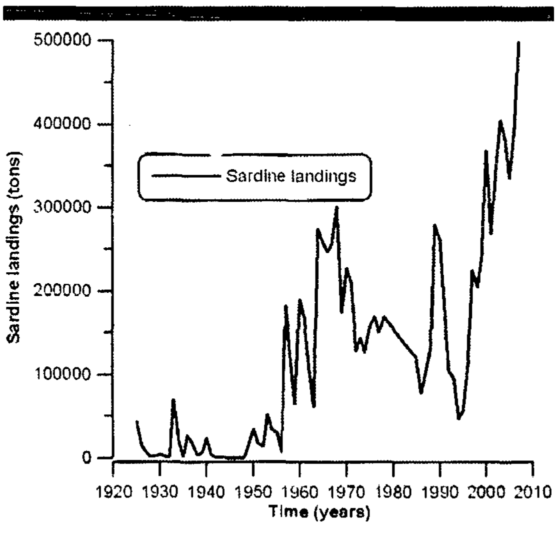

Figure 3. Interannual variability in sardine landing since 1925.

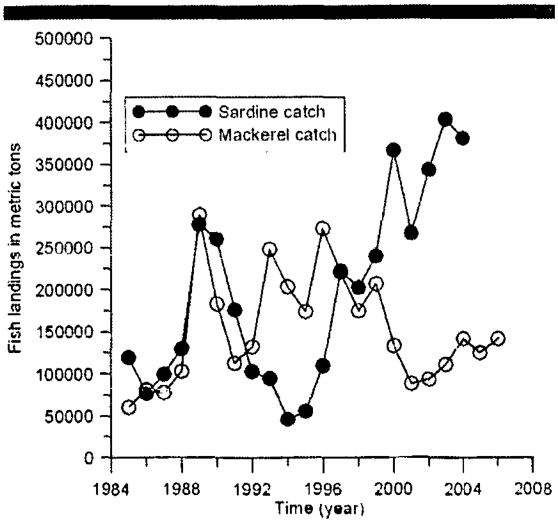

Figure 4. Comparison between sardine and mackerel landings (1985–2006).

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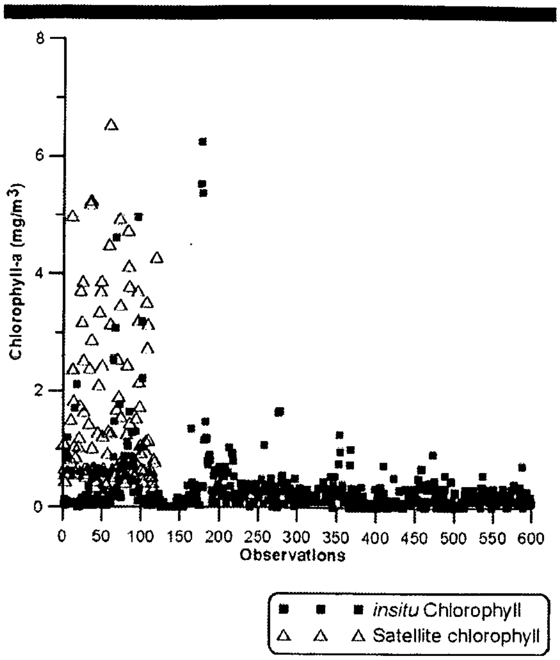

Figure 5. Observed chlorophyll during 1984–2006 for a comparison with monthly *SeaWiFS* chlorophyll values retrieved for the study area (data source: Indian Oceanographic Data Centre, NIO, Goa).

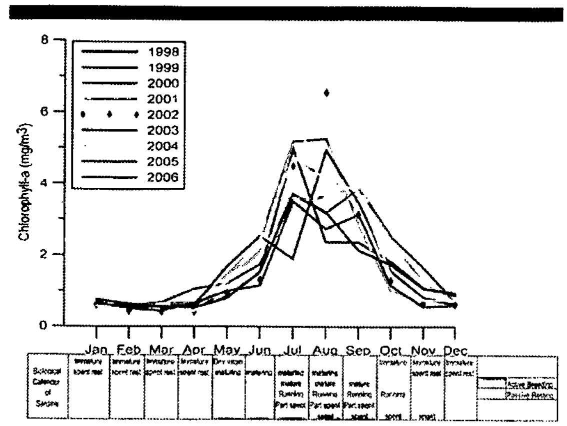

Figure 6. Monthly satellite chlorophyll concentration for the period 1998–2006 in relation to the biological calendar of sardines. Grey coloured columns in the table show the active breeding phase, and remaining columns show the passive resting phase.

concentrations ≥ 1 mg/m^3 can be a threshold mark as calculated for the entire study period (Table 2). The average monthly chlorophyll a values in May reach a threshold level of above 1 mg/m^3 (Table 2). We have examined the suggestion (Madhupratap *et al.*, 1994) that a mismatch *viz.* an early spawning and a time lag in development of food (through a break in monsoon or upwelling) would be detrimental to recruitment.

Sardine Landings *vis-à-vis* Chlorophyll during Bloom Initiation

We tested the null hypothesis that the variability in sardine landings was independent of fluctuations in average chlorophyll concentration during bloom initiation month. We could confirm that 39% variability in sardine landings was related to average chlorophyll a concentration during the bloom initiation month. Figure 7 clearly depicts an increase in chlorophyll a, which is associated with high landings (match), and a decrease with reduced landings (mismatch), except for the year 2002. Since chlorophyll availability cannot be the only factor affecting the sardine biomass, there are other factors also affecting sardine biomass. But the availability of chlorophyll-rich water in the bloom initiation month will result in better survival of sardine larvae. Early food availability provided by an upwelling bloom, indicated as higher chlorophyll a in the chart, is reflected in increased sardine landings, since many of the total larvae recruited were able to survive because of surplus food. Even though *SeaWiFS* data are short, the data do indicate a definite link between chlorophyll a and sardine landings. Early initiation of phytoplankton bloom may not be sufficient to ensure a higher survival of sardine larvae in the same year, but it is definitely a necessary condition as envisaged in the study. This was reflected in the sardine landings, since the fishery was dominated by 0-year class fishes (Table 1). An unprecedented blooming was observed in 2002 when chlorophyll a values were the highest during the study period. Thus, the year 2002 was exceptional to have a low chlorophyll in May followed by an unanticipated high chlorophyll period (Figure 6). Since the spawning period of sardines is protracted, high survival of later spawned larvae in the years when bloom development delayed could make up for poor survival of early spawned larvae.

Gut analysis shows that, being filter feeders, sardines ingest the particulate phytoplankton and zooplankton available in its ambient waters. The phytoplankton bloom (mostly diatoms and dinoflagellates) results in better productivity enhancing the microzooplankton and zooplankton in the Arabian Sea (Madhupratap *et al.*, 2001). This is evident in this study, since zooplankton biomass observations in the study area also show several peak values during the months (September–December) following increased chlorophyll a (Figure 8).

Seasonal Appearance of Sardines and Chlorophyll

The present study clearly reveals the synoptic scale temporal changes (1998–2006) with respect to chlorophyll availability in the three prominent sardine landing maritime states (Figure 9) of India—Kerala, Karnataka, and Goa. Figure 9 illustrates how chlorophyll-rich waters appear earlier in the south (Kerala coastal waters) and move gradually northward, and the pattern reverses during the retrieval of monsoon. The changing intensities of chlorophyll in the coastal waters (area under the graph for each year in Figure 9) of the states describe

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Table 2. *Estimation of monthly average chlorophyll during the study period indicating a higher value above the threshold during the active breeding season.*

Month	Average Chlorophyll (mg/m³) during 1998–2006	Life Stage of Sardines
January	0.618333	immature, spent resting
February	0.540444	immature, spent resting
March	0.546444	immature, spent resting
April	0.593778	immature, spent resting
May	1.158222	maturing, developing virgins
June	1.858333	maturing
July	3.957667	maturing, mature, running, partially spent
August	4.011889	maturing, mature, running, partially spent, spent
September	3.187778	mature, running, partially spent, spent
October	1.666556	immature, running, spent
November	0.937333	immature, spent resting, spent
December	0.708	immature, spent resting

the possible appearance and disappearance of sardine shoals during the active breeding phase.

The variation in quarterly sardine landing in each maritime state (Figure 10) is proportional to the changing intensities of chlorophyll in the respective coastal waters. This shows an aggregation response of sardine larvae to chlorophyll concentrations.

DISCUSSION

There was very little change in the fishing effort during the study period, with 238,772 fishing crafts in 2005 (CMFRI, 2005) in comparison with 239,000 crafts in 1997 (Sathiadhas, 2006). Thus, the increase in sardine landings during the study period, despite steady fishing effort, indicates a direct trophic link as a reason for the revival of the fishery. Sardines possess a fine branchial apparatus and feed predominantly by filter feeding on phytoplankton and zooplankton in ambient waters. Chlorophyll *a* in a given area, as an index of phytoplankton biomass, is capable of assessing the food availability for sardines.

Summer chlorophyll *a* concentration estimates from the study area are reported to be 0.1 to 5 mg/m³ for a normal distribution and can be very high, from 5 to 10 mg/m³, during bloom period (Raghavan *et al.*, 2006). Heavy blooms of *F. oceanica* were observed in 1949 and 1953 during the rebuilding of sardine stock after the population crash of the 1940s (Nair, 1953; Nair and Subrahmanyan, 1955), suggesting and strengthening the view that the advantage of an early bloom is that more larvae will survive which otherwise would have perished due to lack of food.

The life cycle of sardines depicted a clear picture of an active breeding season from May to September. This coincides with

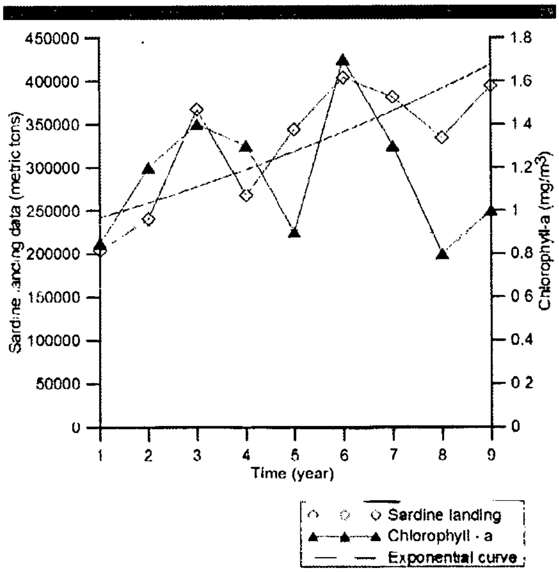

Figure 7. Comparison between chlorophyll *a* concentration during bloom initiation month and sardine landing.

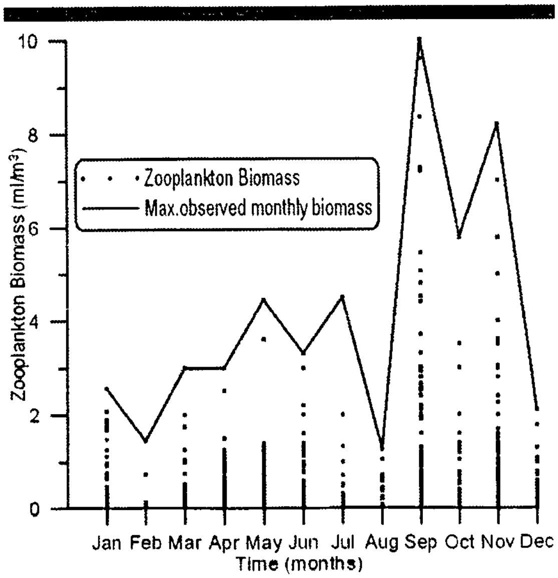

Figure 8. Monthly observed zooplankton biomass during 1984–1996 (data source: Indian Oceanographic Data Centre, NIO, Goa)

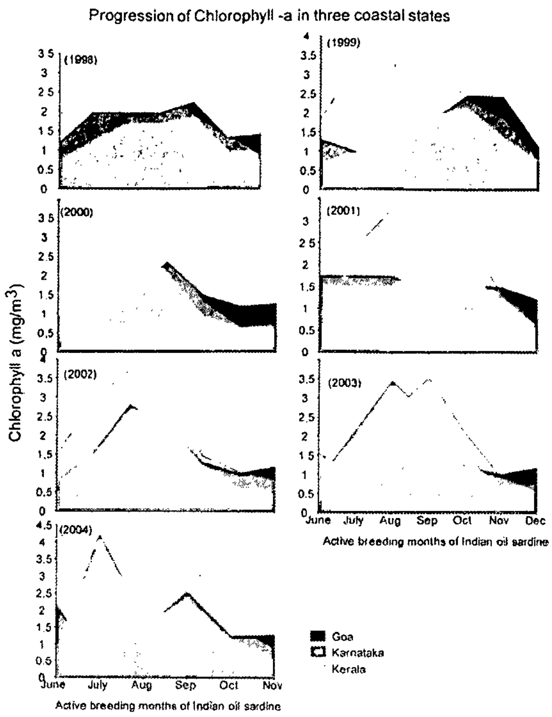

Figure 9. Progression of remotely sensed chlorophyll in the three maritime states during the active breeding season of sardines.

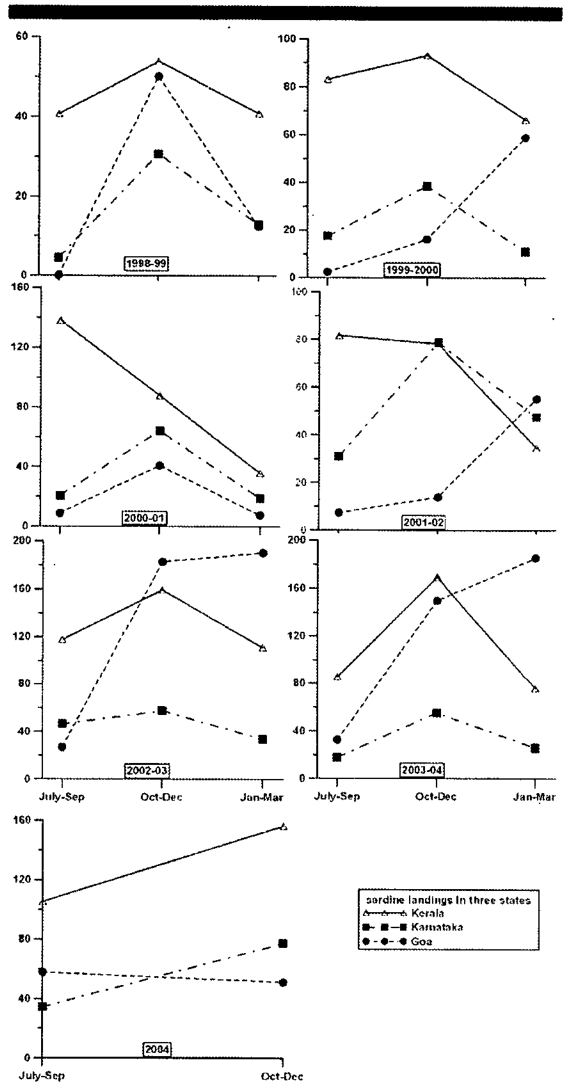

Figure 10. Quarterly sardine landing/km of coastline in the three maritime states.

the high chlorophyll concentration seen during May to October every year. Thus, there is a seamless connection of life history and biology of sardines to phytoplankton bloom dynamics. This supports the finding that the fish itself times its appearance to exploit the productive southwest monsoon period (Madhupratap *et al.*, 1994). The upwelling bloom can be characterized with respect to its peak amplitude, timing of peak, timing of initiation, and duration. In the present study, magnitude of the bloom at initiation is considered for characterization of bloom, which naturally falls in the month of May every year. May is the most critical month for sardines because both bloom initiation and the beginning of sardines' active breeding phase occur during May.

A delay in the initiation of bloom in the area results in hampering the congenial conditions for survival of sardine larvae. In the prevailing rough conditions when fishing activity is slackened, there may be an apparent paucity of sardines. But, as we find in the published reports (Antony Raja, 1969; Longhurst and Wooster, 1990), when there was fishing during July–August, it was noticed that the spawners entered the coastal waters due to increase in food production and migrated beyond the usual fishing belt (30-m depth) for spawning. The spawners again made a reentry to compete with the juveniles for feeding during September to December. The juveniles entered the coastal waters gradually for feeding during January–March and steadily migrated to deeper waters with reduced food. Their disappearance initiates first from the northern limits of sardine fishing ground and ends up in the southern areas later.

Recent works on the survival and early life history of fishes elucidates various factors including predation, drift pathways, and changing environmental conditions in addition to variation in food (Bakun and Broad, 2003; Cury *et al.*, 2000; Houde, 1987; Legget and Deblois, 1994; Miller *et al.*, 1988). Upwelling in the waters of the southwest coast of India is restricted to 5 to 15°N, and the variability in physical parameters is manifested in the chlorophyll intensity (Smitha *et al.*, 2008). A correlation between available environmental datasets (SST, sea bottom temperature, surface salinity, surface dissolved oxygen, bottom dissolved oxygen, pH, nutrients, chlorophyll, zooplankton, rainfall, multivariate *El Nino* Southern Oscillation index, coastal upwelling index, and derived SST) and sardine catch from the study area vividly segregate the significance of chlorophyll from other environmental factors in explaining the sardine catch from the Malabar upwelling area (Krishnakumar and Bhat, 2008). A similar analysis of data sets is redundant in the context of this investigation. Hence, this investigation focused on food alone, the lone implicated factor chlorophyll *a* (as an index of phytoplankton biomass), and explored various avenues of this factor in explaining sardine variability.

A finer scale spatial and temporal pattern of egg and larval stages of sardines in relation to chlorophyll concentration could have yielded a proper model describing the presence or absence of sardines in coastal waters with a definite chlorophyll range. There are sparse reports of sardine eggs from Quilandy (Devanesan, 1943) and Kozhikode (Nair, 1953) and also descriptions of the larval and postlarval stages of sardines in these regions (Nair, 1959). But lack of information on distribution of eggs and larvae emphasizes the need for sampling of early life history stages of sardines over many years for determining the annual condition of larval and juvenile sardines in relation to chlorophyll concentrations.

CONCLUSIONS

Variation in sardine abundance could be attributed to variability in physical forces such as upwelling, sea level, temperature, wind stress, rainfall, and monsoon conditions (Krishnakumar and Bhat, 2008; Longhurst and Wooster, 1990). However, such an indicator was not a direct trophic link to sardines. The important factors responsible for the offshore–inshore migration appear to be the strength, duration of upwelling bloom, and changes it brings about in physicochemical and biological conditions in the coastal waters. But a lag phase between upwelling and intense production is notable in earlier studies in this region (Vimal Kumar *et al.*, 2008). Hence, chlorophyll concentration in coastal waters is the most important factor for establishing a trophic link that summarizes the above physical and chemical process. An early spawning and a time lag in development of food (through a break in monsoon or upwelling) would be detrimental to sardine recruitment Consequently, chlorophyll concentration during the bloom initiation month substantially explains the interannual variability in sardine landings. The spatial and temporal variations in the intensity of chlorophyll in the coastal waters were reflected in the sardine abundance.

Application of remotely sensed chlorophyll provided a putative trophic link for explaining variation in sardine catches along the waters of the southwest coast of India. Remote sensing from satellites offers some solution for the requirement of an entire range of information needed to assess the "changing ocean." But this information has to be coupled with other appropriate biological data for forecasting fish distribution. Thus, satellite chlorophyll in its present state alone cannot be an alternative to *in situ* chlorophyll. The absolute chlorophyll present in CASE II waters often gets challenged by the turbidity contributed by other optical constituents. It is the judicious application of both satellite and observed data that will help in deducing the correct picture. There are many recent developments in building of trophic models of aquatic ecosystems (Hall and Mainprize, 2004). There is potential for satellite phytoplankton data to serve in future as a surrogate for sardine biomass. Usually, investigations in fisheries biology lack time series environmental or other biological data sets (Longhurst and Wooster, 1990; Madhupratap *et al.*, 1994). The combination of satellite data sets with fisheries data can lead to robust conclusions. Longer time series will be required to confirm and determine the large-scale fluctuation in abundance, population crashes, and subsequent revival of this major pelagic fishery in the southwest coast of India.

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Fish larval transport in a macro-tidal regime: Gulf of Kachchh, west coast of India

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ABSTRACT

This study combines observational data with a two-dimensional numerical model results to determine the fate of fish eggs released in the Gulf of Kachchh (GoK), a semi enclosed basin on the west coast of India. Fish eggs were treated as passive particles in the model, and were released from probable spawning sites identified from the field surveys. Areas with retention of larvae above 30% have been demarcated as nursery areas. Most of these nursery areas fall in ecologically significant sites which are rich in mangroves and reefs. We find that about 80% of the particles are retained in the basin for all the three prominent seasons prevailing in the GoK. Complete retention of particles in the southern Gulf region and small quantity of flushing out in the northern boundary of the Gulf could be a major reason for sustaining an abundance of larvae in the southern Gulf. Trawler catch data at various sampling points also suggest abundance of fish in the southern GoK region. Model simulation of fish larval transport in the GoK reiterates the fact that fish larval aggregation occurs in the southern GoK during active breeding phase with varying dispersal patterns from spawning sites. Marine protected areas in the Gulf demarcated based on the ecological significance of sites reasonably corroborate with the areas of likelihood of retention of fish larvae differentiated by the model.

1. Introduction

Mangrove and coral reef ecosystems are the spawning and nursery grounds for a majority of fishes in the tropical coastal waters (Chittaro et al., 2004). The last two decades witnessed rampant destruction of coral reefs and mangrove ecosystem due to anthropogenic pressures and climate change (Chittaro et al., 2004; Mumby et al., 2004). Degradation of these ecosystems resulted in reduced recruitment of fish worldwide (Rogers and Beets, 2001) and it is not very different in the Gulf of Kachchh (henceforth will be termed as GoK in the text), a semi-enclosed basin along the west coast of India (Fig. 1). Establishment of industries very close to the coast resulted in destruction of flora and fauna, which is closely associated with the spawning and larval rearing cycle of fishes. GoK is famous for its fisheries potential (Vijayalakshmi et al., 1993). The collective contribution of fish production in the GoK during 2007–2008 was 18.8% to the total production of Gujarat State. During 2007–2008 total fish landing for Gujarat was 6.77×10^5 t, contributing about 22% to the total Indian production of 30.27×10^5 t. Fisheries management of the GoK is carried out on the archetype that local fishery is well mixed with the open waters, and closed areas are enforced as a protective measure for prospective nursery areas of fish (mangroves and coral reefs) (Singh, 2003). But, there is a possibility of self recruitment of fish taking place in the Gulf waters, which was not established in any of the earlier field studies. The irregular coastline of GoK along with shoals and reefs may trap water and inert particles. A semi-enclosed basin with sufficient retention time could retain fish larvae (Lobel and Robinson, 1986), zooplankton (Boicourt, 1982; Sammarco and Andrews, 1988; Murdoch, 1989; Thiebaut et al., 1994), phytoplankton (Roff et al., 1979) and other neutrally buoyant material (Wolanski and Hamner, 1988; Black et al., 1990).

The pelagic larval phase of fishes is responsible for their dispersion or retention (Cowen and Sponaugle, 2009), and during this phase fish larvae are considered as 'poor swimmers' (Leis et al., 2006) when the hydrodynamic forcing on the larvae exceeds its swimming ability, but there are proven cases where larval behaviour has influenced dispersal trajectories (Chia et al., 1984; James et al., 2002; Cowen et al., 2006; Aiken et al., 2007). The scale and predictability of measured fish larval dispersion or retention remain unknown largely due to the difficulty in measuring dispersion in open marine environments. Utilization of high-resolution biophysical model in estimating dispersal distance or retention time is advantageous as the models allow multiple releases of virtual fish eggs, thus making each individual simulation equivalent to numerous observations of dispersal event. These virtual observations provide information about expected variability in the hydrodynamics, and allow construction of a connectivity matrix with respect to larval dispersal (Cowen and Sponaugle, 2009). A

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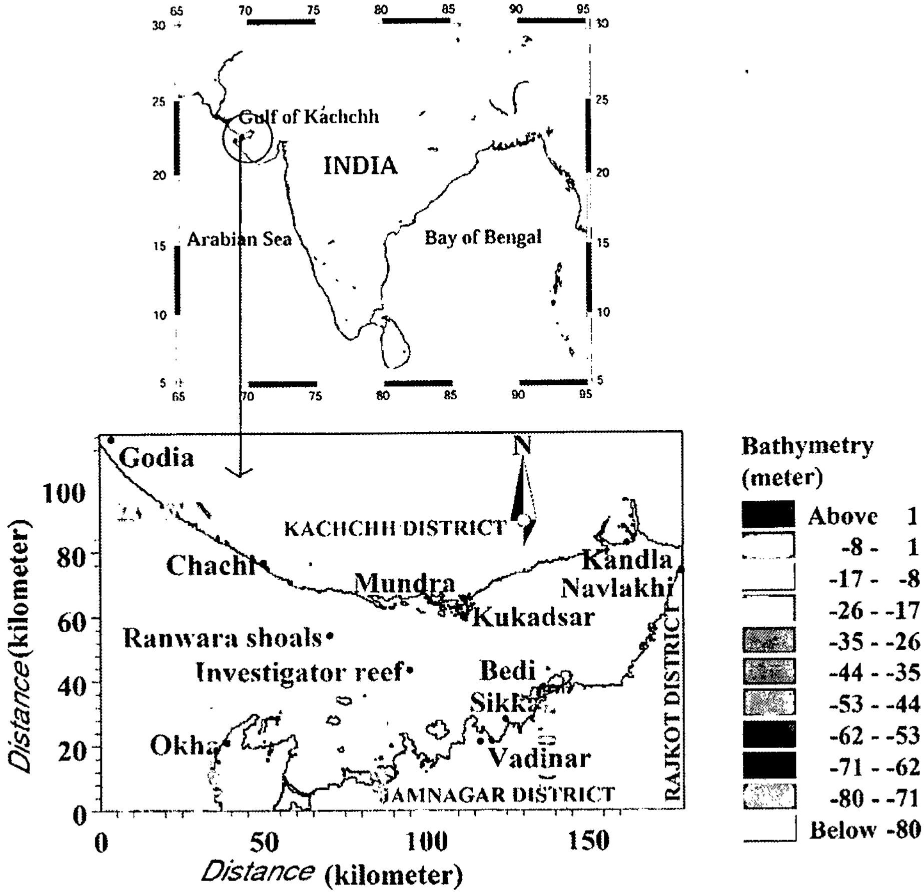

Fig. 1. Gulf of Kachchh and its topographic features.

common strategy employed in this kind of model is to predict the maximum likelihood of retention of investigated species based on habitat attributes (Guisan and Zimmermann, 2000; Moisen et al., 2006; Elith and Graham, 2009). Numerical modelling of fish eggs dispersion at the Patos Lagoon estuary in Brazil was carried out by Martins et al. (2007) using similar methodology.

No study has been carried out so far in the Indian coastal waters to determine the influence of physical forcing on fish larvae under which they are widely dispersed or locally retained. We want to assess whether the abundant fish population in the GoK is a manifestation of self recruitment by fishes trapped due to hydrodynamic or geographical barrier. We have released fish eggs as inert conservative particles from their representative spawning sites under a range of hydrodynamic conditions and associated dispersion processes unique to the GoK to simulate the spreading of eggs and transport of larvae. We have quantified percentage likelihood of retention/dispersal of fish larvae from spawning sites with the aim of identifying potential nursery habitats for fish in the Gulf.

2. Materials and methods

2.1. Study location and ecology

The GoK is located on the northwest coast of India, between 22°15′–23°00′N and 69°00′–70°15′E (Fig. 1), and is approximately 170 km long and 75 km wide at the mouth. Tidal range varies from 3 m at the mouth to 7 m upstream and tidal currents reach up to 2 m/s. The northern Gulf, which is predominantly sandy or muddy and confronted by shoals and creeks, also has large stretches of mangroves. The southern Gulf has numerous islands and inlets that has vast areas of mangroves and reefs with living corals. The southern GoK is a productive spawning ground for fishes with mangroves, coral reefs, seagrass beds and seaweeds. In order to protect the rich biodiversity of GoK, several long stretches of intertidal mudflats and coral reefs along its southern Gulf are declared as Marine National Park and Marine Sanctuary (Fig. 2). A variety of exposed and sheltered sites are present in the GoK and previous studies show the existence of three distinct eddies with diameter varying between 10 and 20 km in the western half of the GoK (Desa et al., 2002; Vethamony et al., 2004; Babu et al., 2005; Kankara

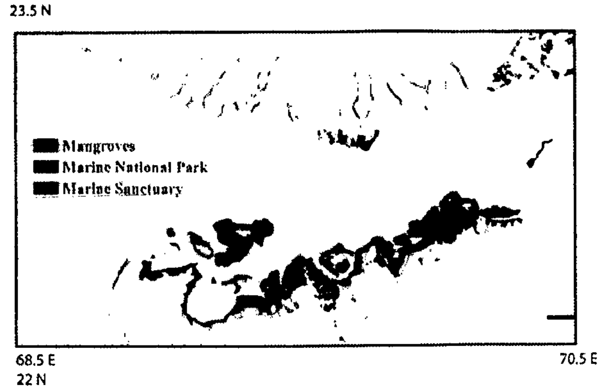

Fig. 2. Distribution of ecologically sensitive areas along the GoK (based on Desa et al., 2002).

Table 1
Four major tidal constituents used in the tidal prediction at the boundary stations.

	Tidal constituents	Dwarka		Godia creek	
		Amplitude (m)	Phase (°)	Amplitude (m)	Phase (°)
1	Semi diurnal Principal lunar component M2	0.823	325	0.864	339
2	Semi diurnal Principal solar component S2	0.293	359	0.333	16
3	Diurnal lunisolar component K1	0.399	54	0.418	64
4	Diurnal Principal lunar component O1	0.195	53	0.211	58

et al., 2007). The high tidal influx covers vast low lying areas of about 1500 km^2, comprising of creeks, marshy tidal flats and rocky regions which provide congenial environment to a wide variety of marine biota.

2.2. Sampling and ancillary data collection

Three prominent seasons namely, pre-monsoon, southwest (SW) monsoon and northeast (NE) monsoon are prevalent in the Gulf (Babu et al., 2005). Hence, recording current meter (model: RCM7; make: Aanderaa, Norway) data measured off Okha, mid-central Gulf and off Kukadsar during April 2002 and November 2002, representing pre-monsoon and NE monsoon seasons, respectively, were used for model validation. The current speed and direction was resolved into u-velocity and v-velocity components representing east–west direction (east is considered as positive and west is negative) and north–south direction (north is considered as positive and south is negative), respectively.

Six sites, A, B, C, D, E and F representing mouth, mid and head of the Gulf in the northern and southern boundaries of the GoK were surveyed for fish egg abundance to identify spawning sites (Fig. 4). Egg samples were collected using a 200 μm mesh size net attached with a pre-calibrated TS flow meter to determine the volume of water filtered. After each (surface, horizontal) haul, the samples were fixed in 5% buffered formaldehyde solution. In the laboratory, an aliquot with a volume of minimum 5 ml was analyzed for enumeration. When the total quantity of sample was more than 5 ml, it was sub-sampled (Folsom plankton splitter) and only a fraction was counted. The samples were transferred to a counting chamber (petridish with a grid of 1 cm^2) for numerically counting the eggs.

Secondary data on fisheries of the GoK were collected from the Department of Fisheries, Gujarat. Trawl catch composition data were collected from Indian Oceanographic Data Centre, NIO, Goa.

2.3. Modelling hydrodynamics

2.3.1. Model domain

Choice of the model domain was supported by the results of a previous study which suggests that eddies near the open boundary of the GoK could possibly reduce the flushing rate, and thus substantially increase the residence time of discharged material in the GoK (Babu et al., 2005). Hence, bathymetry was represented using a regular rectangular Cartesian grid with spacing of 500 m and was created by extracting depth data from MIKE-CMAP and Naval Hydrographic Office (NHO, Dehra Dun, India) charts. The model domain extends 180 km and 120 km in the along-shore and cross-shore directions, respectively.

2.3.2. Hydrodynamic model

Gulf waters are well mixed due to strong tidal currents. Therefore, two dimensional depth averaged models were used in earlier studies in this region to simulate tides and currents, and the model results show agreement with the depth averaged observations (Moller, 1984; Unnikrishnan et al., 1999; Vethamony et al., 2004; Ramanamurthy et al., 2005; Babu et al., 2005; Kankara et al., 2007). Similarly, in the present study we used MIKE 21 – a two dimensional depth-averaged Eulerian time integration scheme – to compute current velocities by solving dynamic and vertical integrated equations of continuity and conservation of momentum (DHI Water and Environment, 2003). MIKE 21 has been extensively used in the simulation of hydrodynamics, water quality, wave dynamics and flow characteristics in estuaries, bays and coastal areas (Chubarenko and Tchepikova, 2001; Babu et al., 2005; Kankara et al., 2007).

2.3.3. Boundary conditions and forcing

As the GoK is a semi-enclosed basin of 170 km long, only mean winds were applied. The two boundary locations at the south and north of the model domain are Okha and Godia, respectively. Tidal elevations at these locations have been predicted using tidal constituents (Table 1) provided by the International Hydrographic Bureau, Spec. Pub., Monaco (Anonymous, 1930) and applied at the south and north boundaries. Predicted tidal elevations of Okha and Godia are linearly interpolated to each grid at the west boundary of the model and applied. Eastern boundaries at Navlakhi and Kandla were closed. Model runs were carried out using the following coefficients: wind friction factor (0.0026), Manning's number (38 m$^{1/3}$ s^{-1}) and horizontal eddy viscosity (0.5 m^2 s^{-1}). Considering the irregular bathymetry, a time step of 30 s was selected and this yielded a Courant number 1.3. There is no significant fresh water run-off into the Gulf (Desa et al., 2002).

2.4. Modelling fish larval transport

2.4.1. Larval transport model

The particle analysis (PA) module of the MIKE 21 (DHI Water and Environment, 2001) has been used to simulate the larval transport in the study region. The model simulates transport and fate of dissolved and suspended substances in the aquatic environment under the influence of fluid transport and associated dispersion processes. It uses the Lagrangian random-walk technique to track the movement of the particles released, and the model has been effectively utilized for tracking the retention or dispersion of hypothetical abalone larvae (Stephens et al., 2006).

2.4.2. Fish eggs and larvae as defined in the model

A total of 27 categories of fish were recorded from the GoK during 1999–2000 with sciaenid (34%) dominating the catch (Vijayalakshmi, 2002). Since croakers belonging to sciaenidae family formed the major component of fishery in the GoK, sciaenid is considered as the bench mark in setting the larval transport model parameters. Therefore, in the present study, for the simulation of fish larval transport, the following assumptions/factors were imposed:

(i) *Period of simulation*: based on planktonic larval duration of the sciaenid, which is similar to other tropical fish species. The larvae complete their planktonic larval duration (PLD) in approximately 20 days, as for most tropical fish larvae (Wellington and Victor, 1989).

(ii) *Particle size of released eggs*: based on the egg size, weight and fecundity of sciaenids. The estimated time of hatch based on the sampling point time was controlled using a source flux defining the mass, with each egg weighing 0.02 mg (Gustavo et al., 2003) as estimated for sciaenid in tropical waters (the most dominant group of fish found in the Gulf) and release of larvae at select spawning sites.

(iii) *Possibility of passive drifting*: based on swimming speed of the sciaenid. The assumption of a purely pelagic phase is supported in some systems, but lab/field observations sometimes contradict the assumption that the larval component is completely passive (Leis, 2006). In a macro-tidal regime like the GoK, weak swimmers will not contribute to dispersal trajectories because of strong currents. Tropical sciaenid fishes have a swimming speed of 0.6–1.4 cm/s (Leis et al., 2006), but the current speed is of the order of 150–200 cm/s.

(iv) *Total particles released*: eggs were estimated based on the fecundity of the sciaenid. Particle release time is based on the spawning time of sciaenid. One particle released in the model is estimated to be equivalent to 100 eggs as fecundity of tropical fishes tend to vary from 0.1 to 1 million (Pandian, 2003). Release of 10 million eggs is achieved by assuming that a minimum of 10 fishes are spawning in a site during the active breeding phase. To visualize the movement of fish larvae, particle-tracking (numerical experiment using PA model) simulations have been carried out for the 6 spawning locations surveyed for egg abundance in the Gulf and tracked for 30 days. Final site selection for egg release in the PA model was decided based on the egg abundance and dispersal pattern observed from the particle tracking results.

(v) Virtual fish eggs are simulated as neutrally buoyant passive particles. In this study, we assume that fish larvae are transported with the flow without settling. Released eggs form larvae in a day in tropical conditions as their hatching time is reported to be less than a day (Pauly and Pullin, 1988). For a smooth illustration of events during larval transport, the tracer particles used in the model are termed as eggs at the spawning site, and larvae thereafter, as eggs develop into larvae in a day in sciaenid fishes. Hence, hypothetical larvae were allowed to disperse following the egg release from two major sites identified for each season. The larvae are tracked hourly in this experiment to identify their patterns of dispersal and retention. Dispersed patterns are presented as snap shots at different time steps (day 1, day 5, day 10 and day 16).

(vi) Active fish larvae tend to migrate vertically. But a well mixed current regime similar to the Gulf tends to carry forward the larvae. The difference in trajectory may result in a shift in their distribution to the order of hundreds of meters, but limitations of a 2-D depth averaged model in a 500 m grid spacing make it difficult to consider this possibility and it is assumed that the changes in distribution of larvae due to vertical migration is negligible for the study.

(vii) The larval abundance in a region is affected by predation, mortality and behaviour. In this study, these aspects were neglected as the variation in these parameters in the study domain is not known, and it is difficult to interpolate the same in spatial scales in the numerical model.

2.5. Model parameters evaluation

The quality indices used for comparing model results with measurements are *bias* (*mean error*), *Root Mean Square* (*RMS*) *Error* and the *correlation coefficient* (r). For each valid measurement, me_{ij}, measured at time t_{ij}, the corresponding model value, mo_{ij}, is extracted from the model results using linear interpolation between the model time steps before and after t_i. The quality indices are calculated as follows: $dif_i = mo_i - me_i$; *Mean*, $\overline{me} = (1/N)\sum_{i=1}^{N} me_i$; *bias* $= \overline{diff} = (1/N)\sum_{i=1}^{N} dif_1$; *RMS* $= \sqrt{(1/N)\sum_{i=1}^{N} dif_i^2}$.

2.6. Model application

The concentration expressed as the percentage of hypothetical larvae for each unique hydrodynamic simulation was extracted at various sampling stations to assess the intensity of retention/dispersal under the influence of flow and the associated dispersion processes. Since the model uses the Lagrangian random-walk technique to track the movement of the particles defined, the same can be effectively utilized for tracking the retention/dispersion of hypothetical fish larvae released within the domain. The simulation results of larval dispersion carried out in the GoK were analyzed to assess the fish larval dispersion and their areas of likelihood of retention for different seasons from the possible spawning sites.

3. Results and discussions

3.1. Model evaluation of flow pattern and residual eddies in the GoK

The modelled tidal elevation at select stations agrees with the measured surface elevation (Fig. 3a). The modelled u and v current components also agree with the measured current components (Fig. 3b and c). Correlation coefficients of 0.59 and 0.54 have been obtained between measured and modelled ebb and flood currents, respectively. There is slight over-estimation of modelled flow velocities for ebb and flood with a bias of 0.06 and 0.12 m/s, respectively. The RMS error observed for ebb and flood velocities are 0.18 m/s and 0.25 m/s, respectively. Table 2 indicates that the model reproduces surface elevation and currents accurately in the entire model domain. Results show strong east–west component and weak north–south component in the Gulf. Flow patterns in the Gulf have been simulated (Table 3) for the three seasons, namely, pre-monsoon (April 2002), SW monsoon (June 2002) and NE monsoon (October 2002). The residual velocity is important in understanding the transport of eggs or larvae discharged in a coastal environment. Residual velocity is driven by density gradients and tides. Since the Gulf is a well mixed basin, density gradient contribution to the residual current is ignored and tide induced residual currents are analyzed. The residual velocity field computed from the model results confirmed the existence of three distinct permanent eddies with diameter varying between 10 and 20 km in the western half of the Gulf, an anti-cyclonic eddy south of Ranwara shoal, a cyclonic eddy east of it and another anti-cyclonic eddy located between the cyclonic eddy and the investigator reef (Vethamony et al., 2004; Babu et al., 2005).

3.2. Spawning sites and nursery grounds

The 6 sampling sites (A, B, C, D, E and F) surveyed for fish egg abundance (Table 4) are along the Gulf coast and away from the influence of strong currents *viz.*, mid-channel and eddies of the Gulf. Particles released from sites A, B, E and F (Fig. 4) experienced wider dispersal pattern than at sites C and D. Hence, the sites A, B, E and F have been selected as spawning sites based on particle tracking studies. During NE monsoon, eggs are retained in the southern Gulf due to predominant winds from NNW (340°) (Fig. 5) ruling out the importance of spawning sites at E and F. Our field surveys also indicated higher egg abundance at sites B and F during

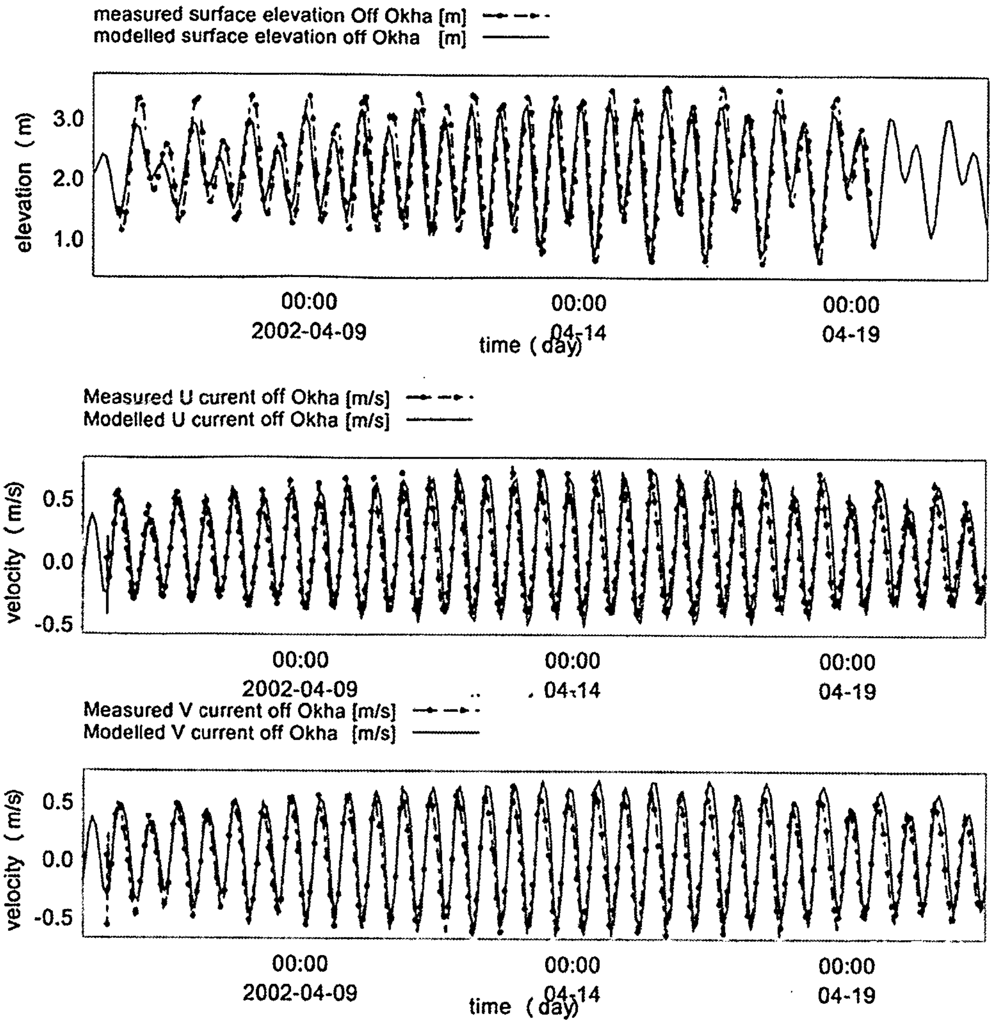

Fig. 3. Comparison between modelled and measured (a) surface elevation, (b) current speed and (c) direction.

NE and pre-monsoon, and these sites are showing wider dispersal patterns (Table 4). Based on these considerations, it was decided to consider the spawning sites at B and F for egg release. Site A was selected for all the 3 seasons as particle trajectory revealed dispersal in all the 3 seasons when particles were released and tracked from this site (Fig. 4). Thus, particles were released from two sites (F and A during pre-monsoon and SW monsoon and B and A during NE monsoon). Since egg abundance data were not available for SW monsoon season, spawning sites were assumed to be the same as pre-monsoon period. Primary nursery areas are those areas in the estuarine system where initial post-larval development takes place. These areas are usually located in the uppermost sections of a system where populations are uniformly very early juveniles. In this study, nursery areas are defined as those areas where ≥30% likelihood of retention of larvae is simulated (Fig. 7). The numerical experiments show that these nursery areas are distributed in the ecologically sensitive regions (Fig. 2) along the GoK, except for the northwestern part of the Gulf.

3.3. Fish larval dispersion/retention

Pre-monsoon: There was uniform dispersal of particles along the northern and southern boundaries of GoK in the pre-monsoon season (April), and less than 20% of particles exited along the northern boundary to the open waters. The number of exited particles is negligible in comparison to those spread along the boundaries of GoK (Fig. 6a). The particles dispersed along the southern boundaries remained within the domain. Thus, it can be inferred from the numerical experiment that the fish eggs released along the southern boundaries of the Gulf tend to remain in the region, whereas the eggs from spawning sites in the northern Gulf does not remain within the Gulf. The northwestern boundary of the Gulf near

Table 2
Comparison of model results and observations off Okha during April 2002 for currents and water elevation.

Parameters		Mean	Bias	*RMS*	Correlation coefficient	No. of time steps
Current speed (m/s)	Ebb	0.41	0.06	0.18	0.59	1166
	Flood	0.45	0.12	0.25	0.54	1183
Surface elevation (m)		2.16	0.06	0.39	0.87	1295

Table 3
Characteristic flow pattern for different seasons (currents measured at every 10 min interval using recording current meter (model: RCM7; make: Aanderaa, Norway) during April 07–16 and November 06–30, 2002 are used).

Season	Wind speed (m/s)	Wind direction (°N)	Off Chachi			Mid-channel				Off Kukadsar					
				Max. current speed (m/s)		Predominant direction (°N)		Max. current speed (m/s)		predominant direction (°N)		Max. current speed (m/s)		predominant direction (°N)	
			Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	Ebb	Flood	
Pre-monsoon	4.5	WNW (292°)	Measured	0.72	0.67	300	120	1.37	1.35	265	90	0.86	0.87	235	55
			Modelled	0.75	0.77	295	115	1.63	1.64	265	90	0.87	0.77	230	50
SW-monsoon	6.5	SSW (247°)	Modelled	0.80	0.88	290	110	1.06	1.09	275	105	0.89	1.3	340	140
NE-monsoon	3.5	NNE (337°)	Measured	1.08	1.12	290	110	1.88	1.67	260	100	1.28	0.91	240	55
			Modelled	0.91	1.3	290	110	1.19	0.94	270	105	0.81	1.3	340	140

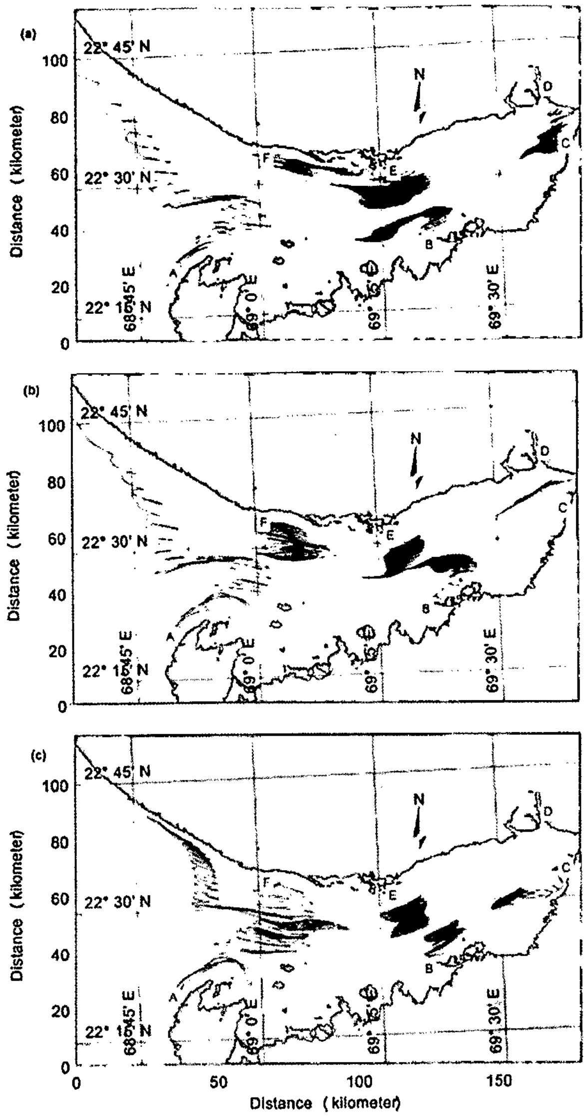

Fig. 4. Simulation of particle trajectories from various sampling stations: A – okha, B – Bedi, C – Navlakhi, D – Kandla, E – Kukadsar, and F – Mandvi: (a) April 2002, (b) June 2002 and (c) November 2002.

spawning site 'F' is a crucial nursery ground during pre-monsoon and SW monsoon season. But, this area is not regulated for fishing. Fish egg abundance survey also corroborates the numerical simulation.

SW monsoon: Particles trajectories were simulated for this season to observe the influence of SW-monsoon (June) on fish larval transport. The particles were dispersed from the spawning sites predominantly south of GoK. Those released in the north being retained with larger larval retention on the reefs (Fig. 6b) in contrast to a wider dispersal as seen during pre-monsoon season. Less than 10% of larvae exited the domain during the SW-monsoon season. The westward movement of larvae is restricted by the predominant SW winds, and only a small percentage of larvae exited the domain. Similar to pre-monsoon season, the particles dispersed along the southern boundaries remained within the domain.

NE monsoon: The particles dispersal during the NE monsoon (November) followed the pattern of previous seasons for the station close to Okha (site A). But, at station close to 'B' the particle release showed retention in and around the release site without

Table 4
Fish egg abundance (in numbers) and site ecology as observed during an exploratory survey during April and November, 2002.

Site		Egg abundance (number/100 m^3)		Site features	Geographical barrier	Fishing activity
		April 2002	November 2002			
A	Off Okha	0	114	Uneven topography with strong currents	Free flushing in and out with ebb and flood	Less commercial fishing operations
B	Off Bedi	60	3177	Scattered reef and mangrove areas along the coast	Small islands and reefs scattered in the Marine National Park area	Commercial fishing operations active
C	Off Navalakhi	454	60	Closer to the land area and depth gradually taper to the minimum	Extreme south eastern boundary with a tidal variation of 7.31 m for mean high high-water	Only port in Rajkot district with some fishing activities
D	Off Kandla	35	0	Alluvial marshy tidal flats with a major creek system	High tidal movements and unusually strong currents	Less fishing except for shore-based hand-net and gill-net
E	Off Kukadsar	0	0	4 major streams, 2 shoals, 2 creeks and a couple of islands with tapering pieces of lands regularly visited by migrating flamingoes	Presence of tapering land, islands and shoals restrict proper flood and ebb flows	Fishing by trawlers is common off Kukadsar
F	Off Mandvi	140	8	River Rukmanathi joins the GoK at this site	Weather conditions hostile except for September to February	Fishing grounds have been identified off Mandvi and fishing pressure is increasing

much dispersal (Fig. 6c). Less than 10% of the particles exited the domain as in the case of SW monsoon season.

3.4. *Redistribution of the fish larvae to nursery grounds*

Particles move along with the tidal currents, which is the dominant hydrodynamic force in the GoK. Since eddies are present in the western region of the GoK, i.e. near the open boundary, it is possible that these eddies could effectively reduce the flushing rate, and thus substantially increase the residence time of discharged materials in the Gulf (Babu et al., 2005). Ebb currents promote less than 10–20% of the accumulated particles to escape out of the domain along the northern boundary without entering into the eddy region (Fig. 7). The particles redistributed along the southern Gulf remained in the region without being flushed out.

In general, particles released at the GoK mouth were pushed along with flood currents into the Gulf. This particle dispersion suggests that the fish eggs after hatching may be dispersed into northern and southern boundaries, rich in reefs and mangroves. However, during pre-monsoon season their entry and exit were partially prevented by the residual eddies at the Gulf-mouth, and this is evident in the particle trajectories (Fig. 4). The flow pattern in the GoK can be visualized like a concentric circle with maximum currents in the mid-Gulf and minimum towards the periphery (Fig. 8). It is observed that the particles, which are released in the inner Gulf moved further into the eastern Gulf. Simulation experiment was repeated after releasing the particles during flood and ebb tides as well. The transport of particles is highly variable with time and space in accordance with tides and currents. Across the Gulf and along the Gulf, maximum excursion of particles is seen during pre-monsoon season. In general, it can be inferred that the spawned fish egg and hatched-out larvae are retained in the GoK domain when released in the interior stations, close to the eastern boundary of the Gulf.

Trawler catch data at various sampling points suggest higher abundance of fish in the southern GoK region (Fig. 9). This possibly could be explained as an outcome of excess fish larval retention in the southern Gulf. In the case of sciaenids, the juveniles and adults have similar preferences for habitat (Johnson and Seaman, 1986). They tend to spawn and live in particular estuaries, and

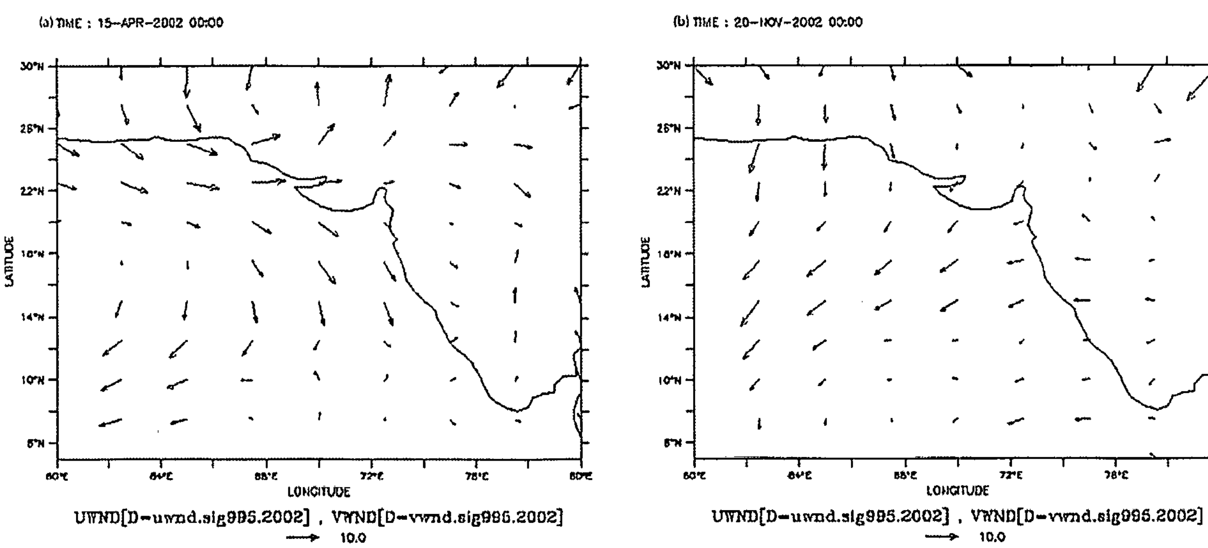

Fig. 5. Wind pattern in the GoK region during pre-monsoon and NE monsoon seasons.

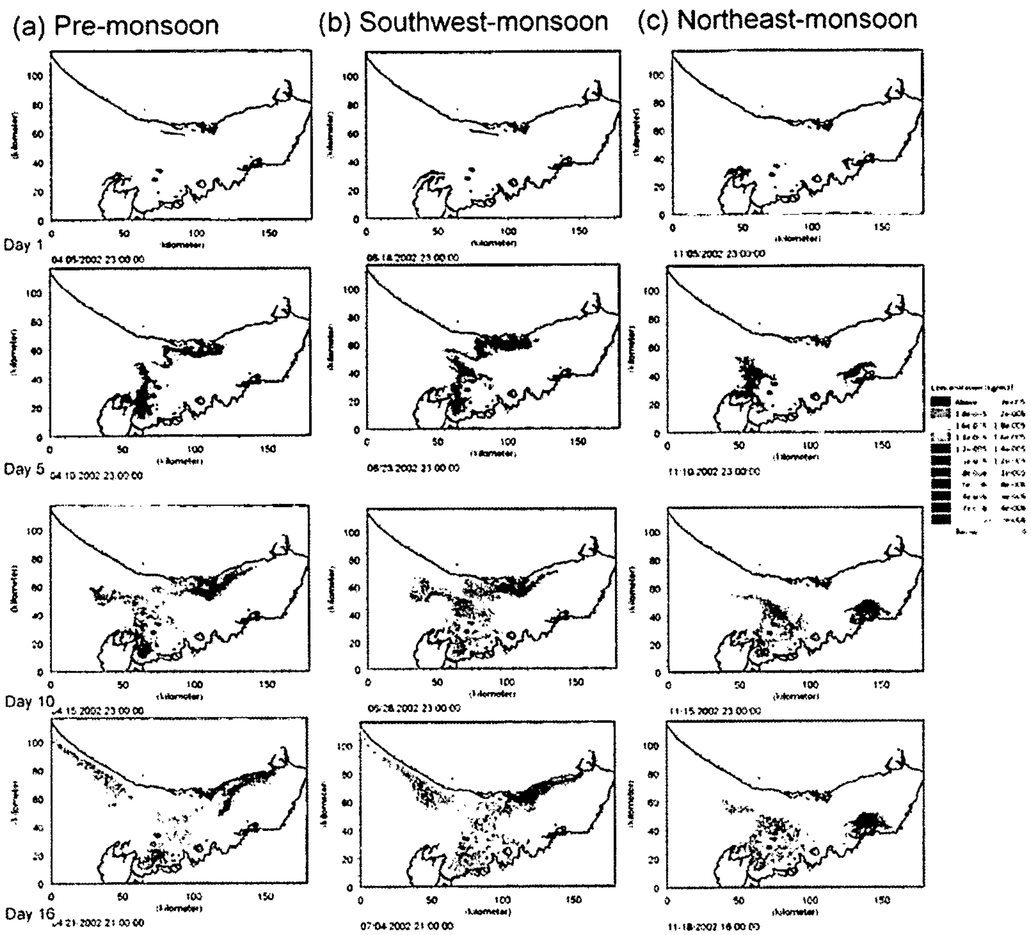

Fig. 6. Simulation of larval dispersal on days 1, 5, 10 and 15 at the GoK: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon.

never migrate to longer distance. The numerical simulation also corroborates maximum particle retention in the southern Gulf in comparison to the northern Gulf. In the northern Gulf, 10–20% of redistributed particles escaped along the northern boundary. In the GoK, spawning sites may vary with seasons, but the dispersal of larvae occurs in such a way that larvae reach nursery grounds in the GoK rather than being dispersed in the open ocean off GoK.

Even though geographical barriers are also imperative in larval retention, their role is superseded by the local hydrodynamics in the Gulf. The particle dispersions from the same spawning site showed variations with changes in hydrodynamic conditions (Figs. 6 and 7). The abundance of fish along the southern region is a clear indication of a driving force which redistributes the fish larvae to ecologically sensitive mangrove and reef areas in the GoK. Thus, the model simulation of particle transport in the GoK reiterates the fact (known biologically) that larval aggregations are going to occur in the southern GoK during active breeding phase of fishes with varying dispersal pattern from the spawning sites. The fish larval abundance in the Gulf is qualitatively inferred and the accuracy of modelled particle with the larvae at field level cannot be quantified on real time basis. But, the results definitely indicate the effectiveness of this tool.

Larval movements of icthyoplankton can be simulated as they are passive, and drift along with the prevailing currents. But juve-

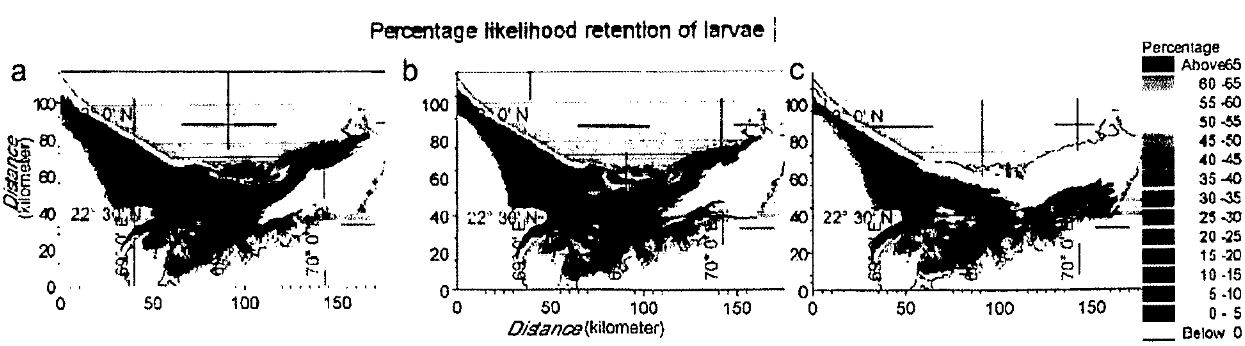

Fig. 7. Likelihood retention of fish larvae at the GoK: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon.

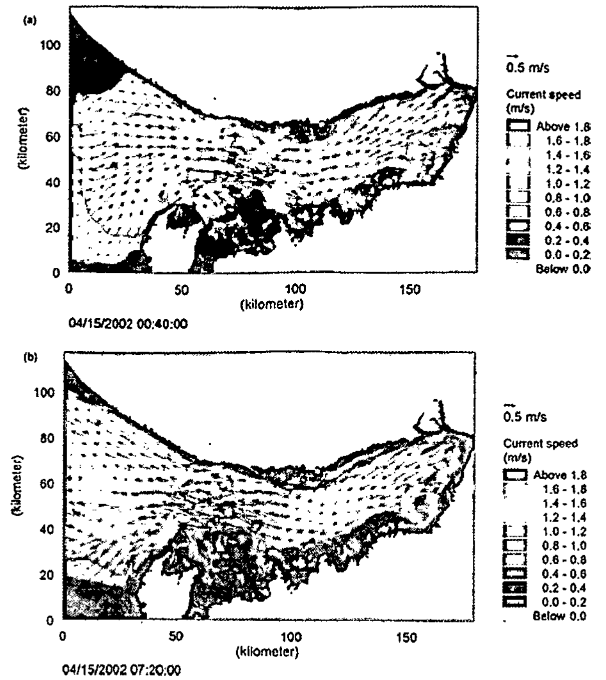

Fig. 8. Typical (a) flood and (b) ebb patterns during spring tide off Okha (April 2002).

nile fishes after planktonic phase cannot be traced with the help of current movements as they acquire swimming speeds that are able to counter the currents. Predation, productivity changes, fishing effort and environmental changes will affect the abundance pattern which is not incorporated in the numerical model. In protected areas like a Gulf, the areas of likelihood of retention of planktonic larvae may have an impact on the fish abundance as the nursery areas can also become their possible rearing grounds. But, there are uncertainties involved in this hypothesis. However, a proper demarcation of potential nursery grounds is definitely an outcome of these modelling studies (Fig. 7). Protecting these nursery areas as a part of the fishery management measure may improve the fish abundance, and also juvenile fish retained in a productive area tend to remain in the same area. The existing fisheries management strategy in the Gulf is based on demarcation of the ecologically significant sites, which is not flawless. There are possibilities of nursery grounds shifting from ecologically significant sites due to changes in hydrodynamic patterns. This limitation can be rectified when nursery ground locations are identified based on likelihood of retention areas from a validated numerical model. This study corroborates not only the ecologically significant sites prioritized by fishes, but also a few additional nursery grounds generated from the model and confirmed in the field (Figs. 2 and 7).

The seasonal changes in spawning sites by fish may be an adapted strategy in the Gulf to cope with the changes in current pattern to advect the eggs from a safe spawning site to a productive rearing area in the Gulf. A lot of uncertainties are involved in explaining this assumption, but the observations are evident enough to prove this changing pattern. The calibrations required for a model to estimate the water quality and productivity of a semi-enclosed coastal environment is complicated as suggested in a previous study along the western coastal waters of India (Menon, 2004). The present study invokes the idea that the demarcation of marine protected areas should be based on the rationale that areas of maximum likelihood of retention of icthyoplankton will be a better fisheries management strategy for the Gulf, imbibing the concepts of an ecosystem-based spatially structured approach (Richardson et al., 2010).

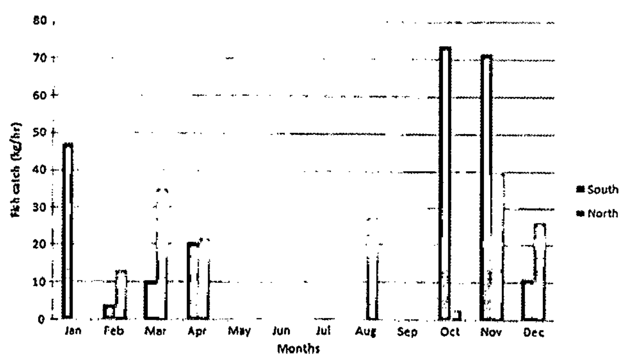

Fig. 9. Trawl catch variation in the northern and southern GoK.

4. Conclusions

The study shows that particle transport modelling can be an effective tool and decision support system in identifying the locations that are potential nursery areas for fish larvae. Management measures like demarcation of closed areas and closed seasons can be implemented in the Gulf based on this tool. The spawning sites may vary with seasons, but the dispersal of larvae ensures that larvae reach nursery grounds in the GoK rather than getting dispersed in the Gulf mouth. The fish larval abundance or aggregation during the different seasons studied suggests the priority areas of likelihood of larval retention. Presently, regulations are enforced only in the Marine National Park and Marine Sanctuary areas in the southern Gulf, which is also an area of maximum retention. Thus, the model demonstrates quantitatively a definite pattern on redistribution of fish larvae in the southern Gulf leading to more abundant fish populations. Hitherto, a significant percentage of particles (≥30%) are retained at two other locations *viz.*, areas beyond three eddies inside the Gulf and upper north-western boundary of the Gulf which are not regulated for fishing. This stipulates the necessity of enforcement of fishing regulations in these areas also, during pre-monsoon and SW monsoon seasons (Fig. 7) for ensuring sustained fishery in the region.

Conflict of interest statement

No competing financial interests exist.

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