

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

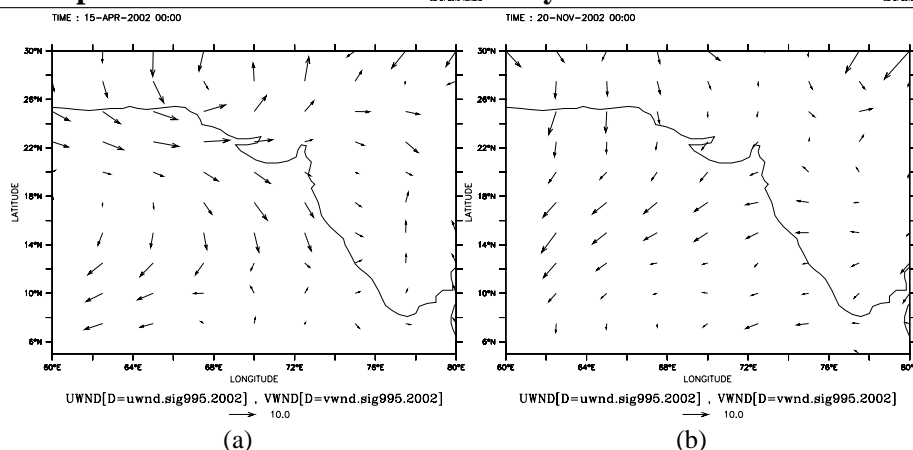


Figure 5.1: Wind pattern in the GoK region: (a) during NE monsoon and (b) during pre monsoon season

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°) (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 because B is surrounded by shoals, where currents are relatively weaker– a favourable condition for accumulation.

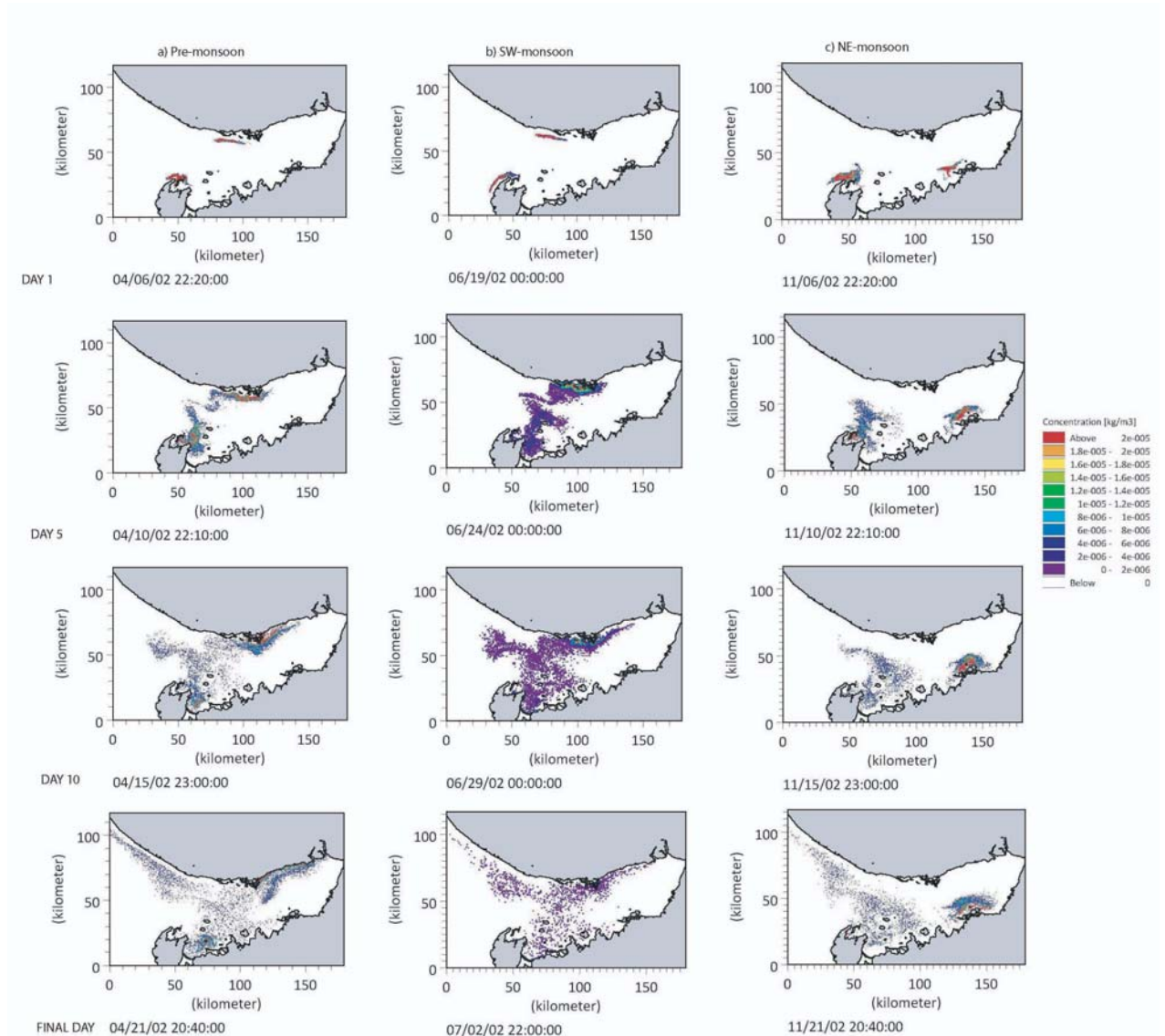


Figure 5.2: Simulation of larval dispersal on day 1, 5, 10 and 16 in the GoK: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon

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

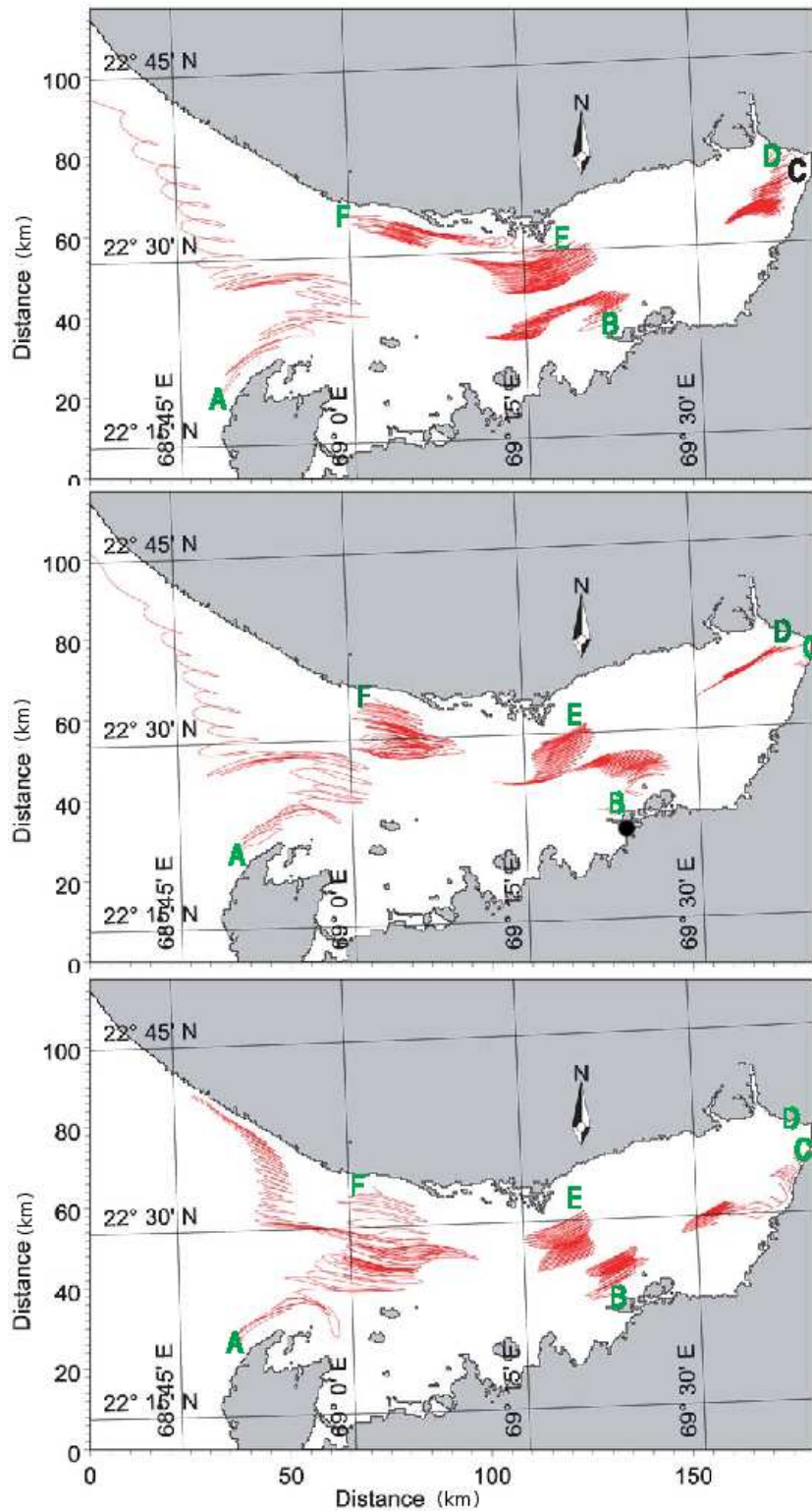


Figure 5.3: Simulation of particle trajectories from various sampling stations: A-off Okha, B-off Bedi, C-off Navlakhi, D-off Kandla, E-off Kukadsar, and F-off Mandvi: (a) April 2002 (b) June 2002 and (c) November 2002

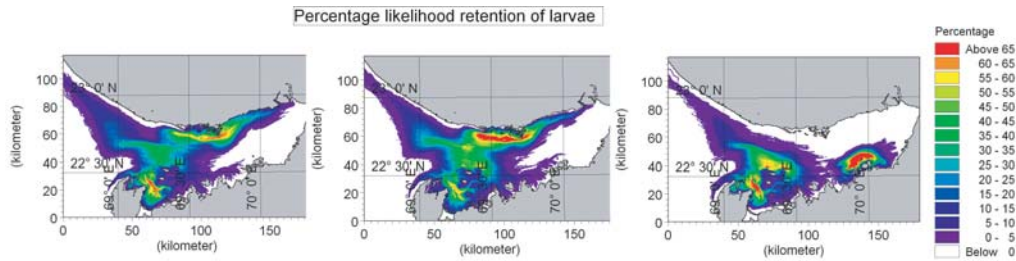


Figure 5.4: Simulation of likelihood of retention of fish larvae in the GoK during: (a) Pre-monsoon, (b) SW monsoon and (c) NE monsoon

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 ichthyoplankton 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 ichthyoplankton will be a better fisheries management strategy for the GoK, imbibing the concepts of an ecosystem-based spatially structured approach.

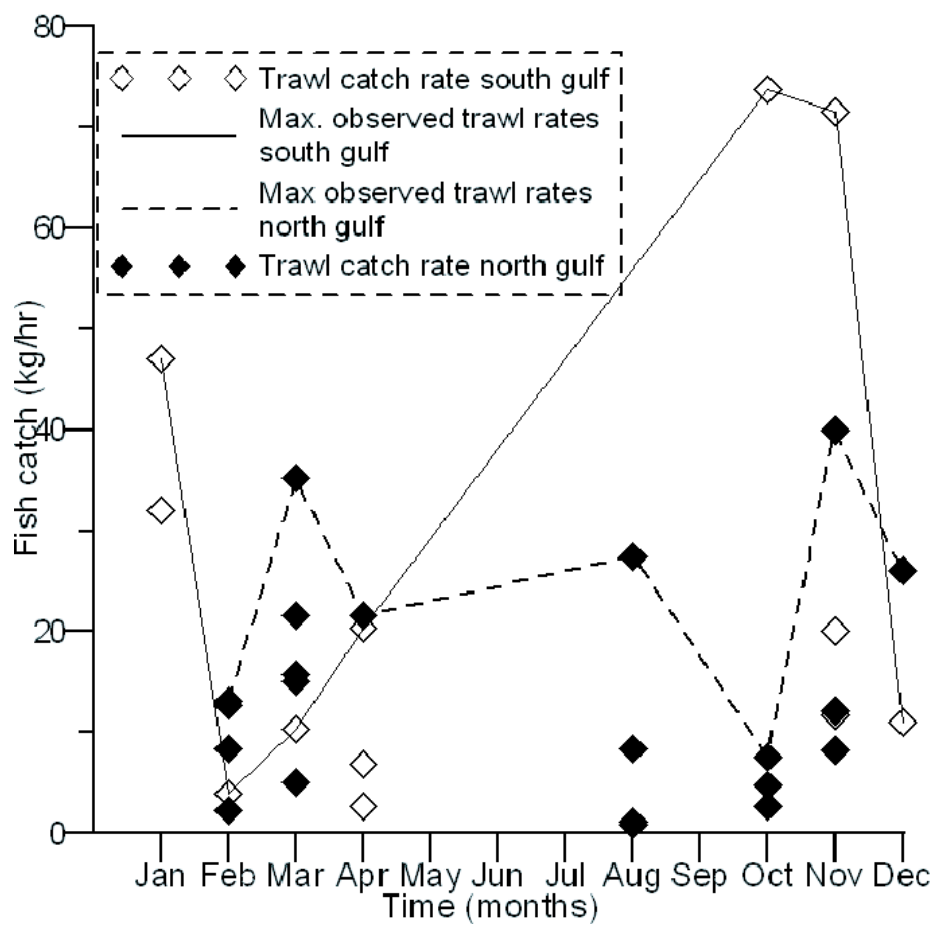


Figure 5.5: Trawl catch variation in the northern and southern GoK

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, meso-scale 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]. Con-

cerning 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.

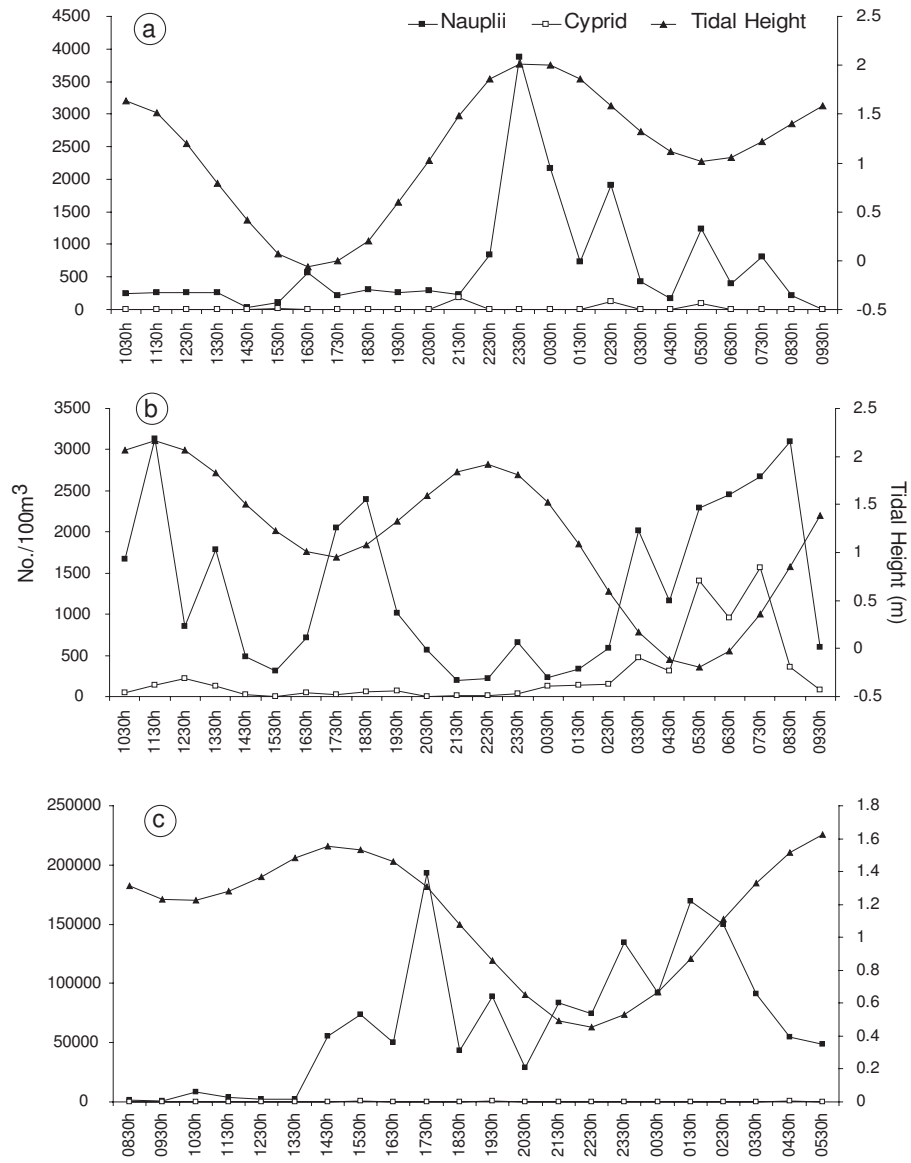


Figure 5.6: Larval abundance noted during the sampling survey in Mandovi and Zuari

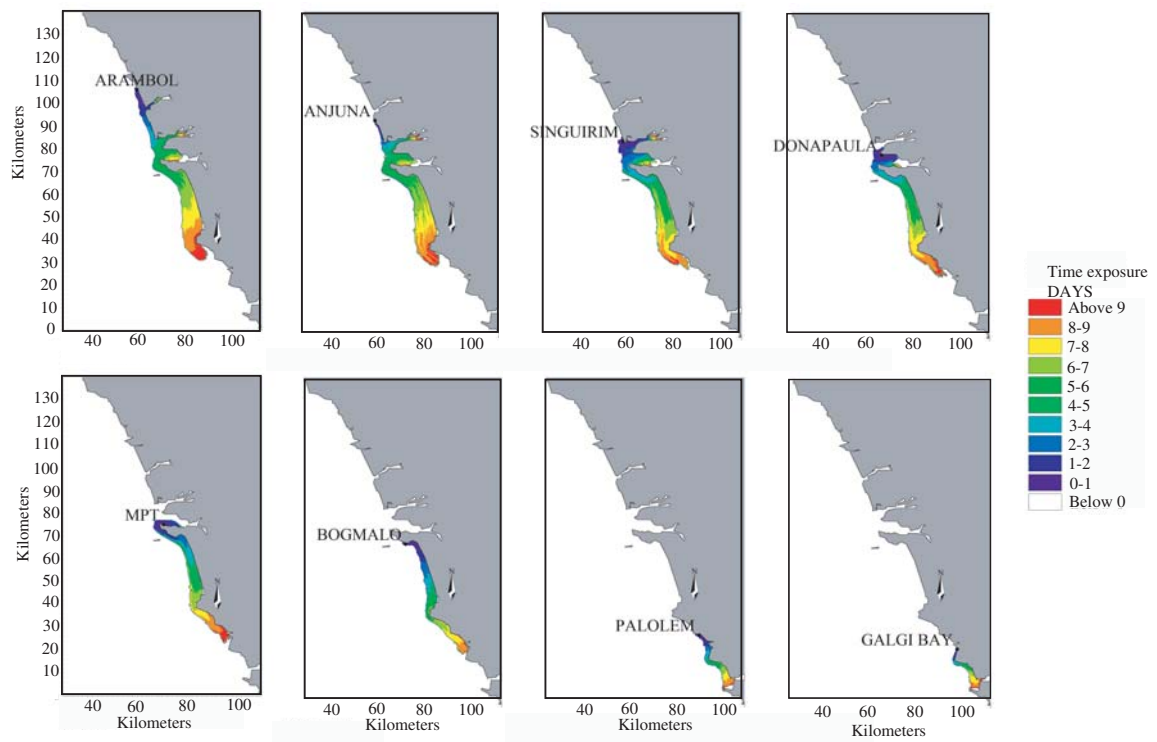


Figure 5.7: Barnacle larval transport during NE monsoon period along the coastal stretch of Goa

(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 $5-8 \text{ m.s}^{-1}$. 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).

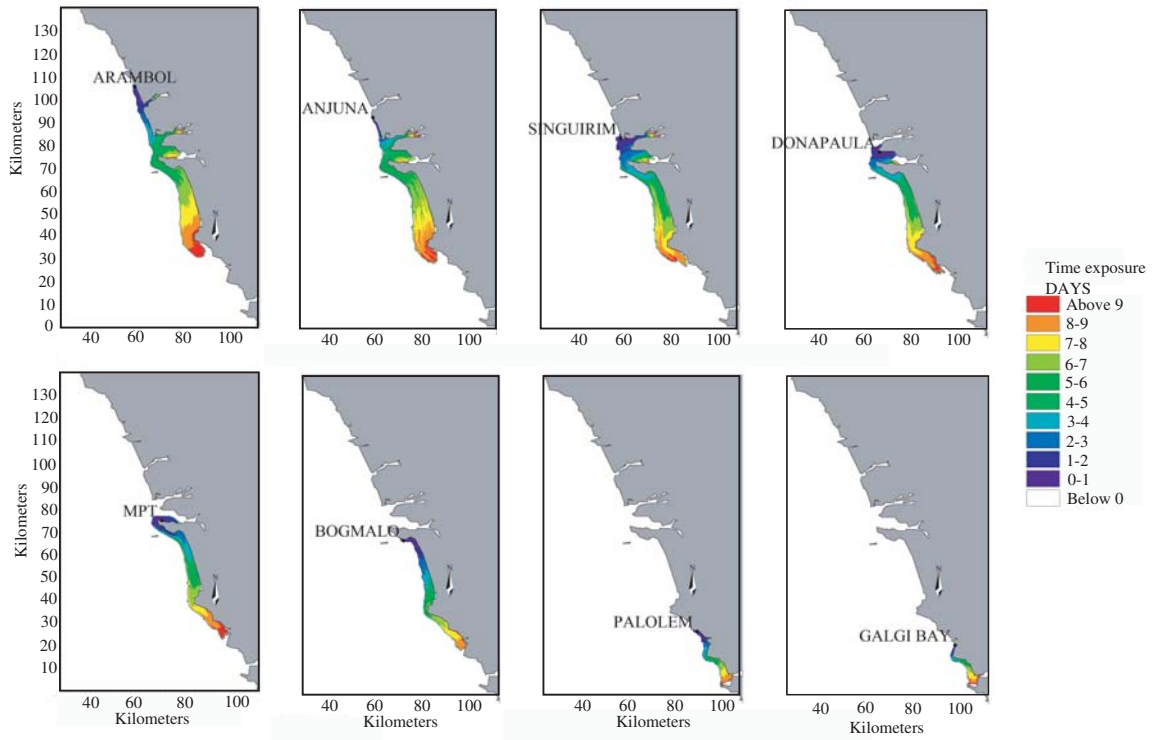


Figure 5.8: Barnacle larval transport during pre monsoon period along the coastal stretch of Goa

(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).

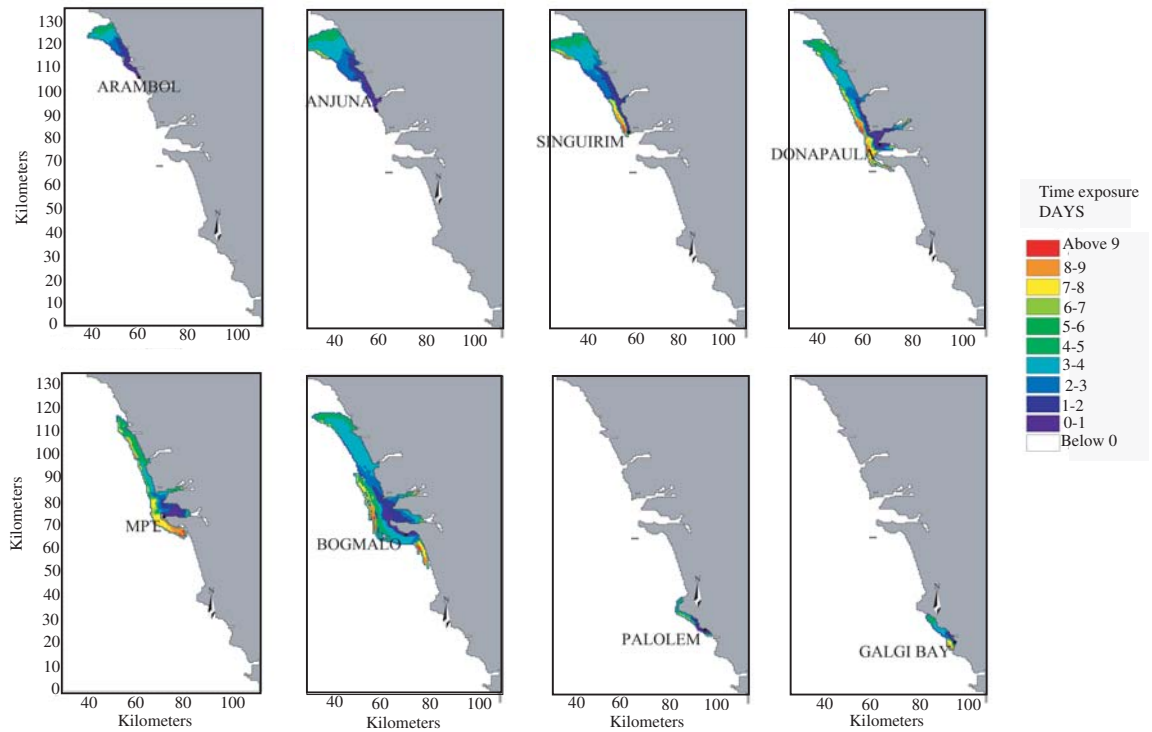


Figure 5.9: Barnacle larval transport during pre monsoon period along the coastal stretch of Goa

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 particles 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 occurred in the Zuari estuary. The particles released from spawning sites moved towards the Mandovi estuary during NE monsoon and pre monsoons.

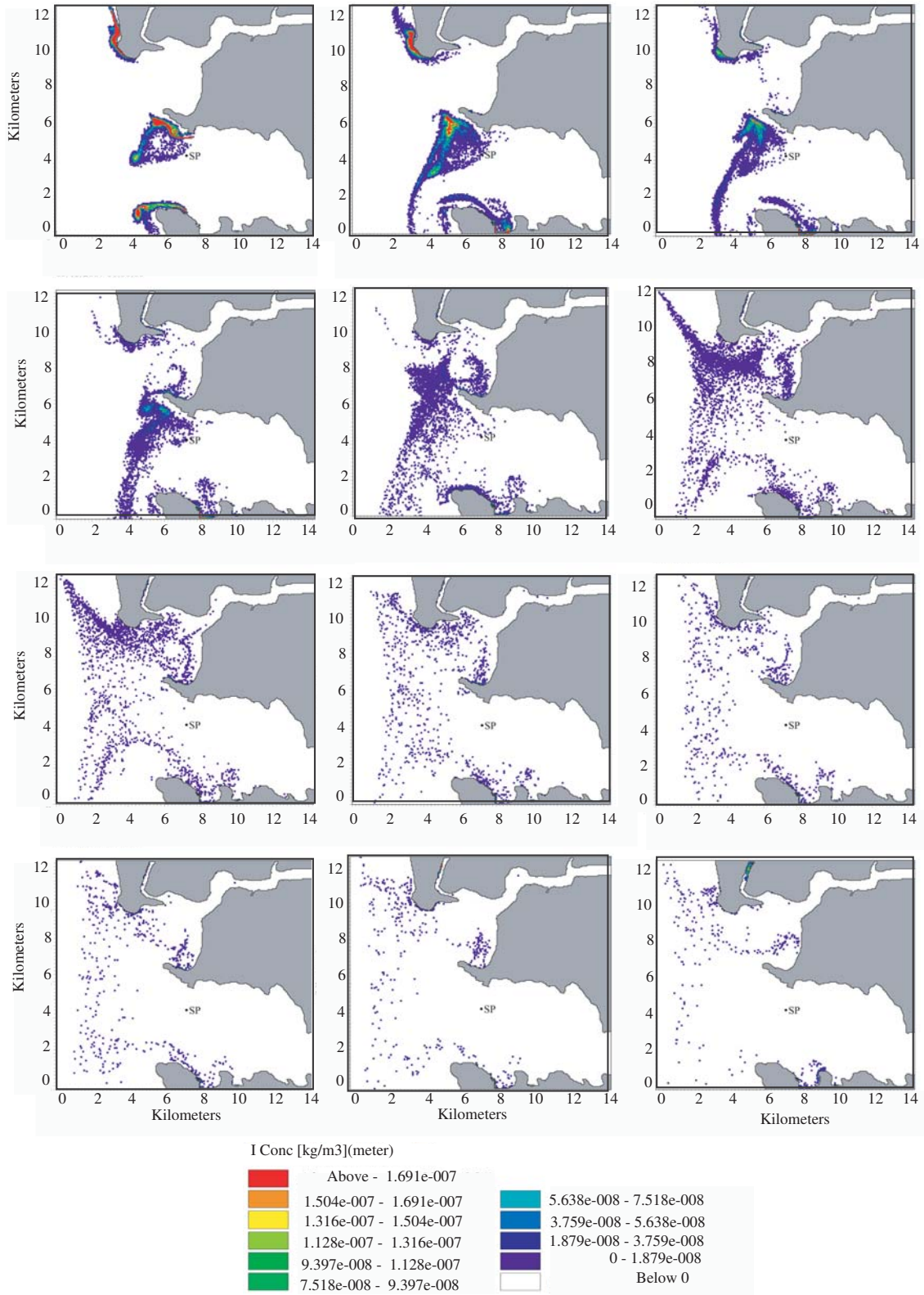


Figure 5.10: Barnacle larval transport during pre monsoon period in Mandovi-Zuari

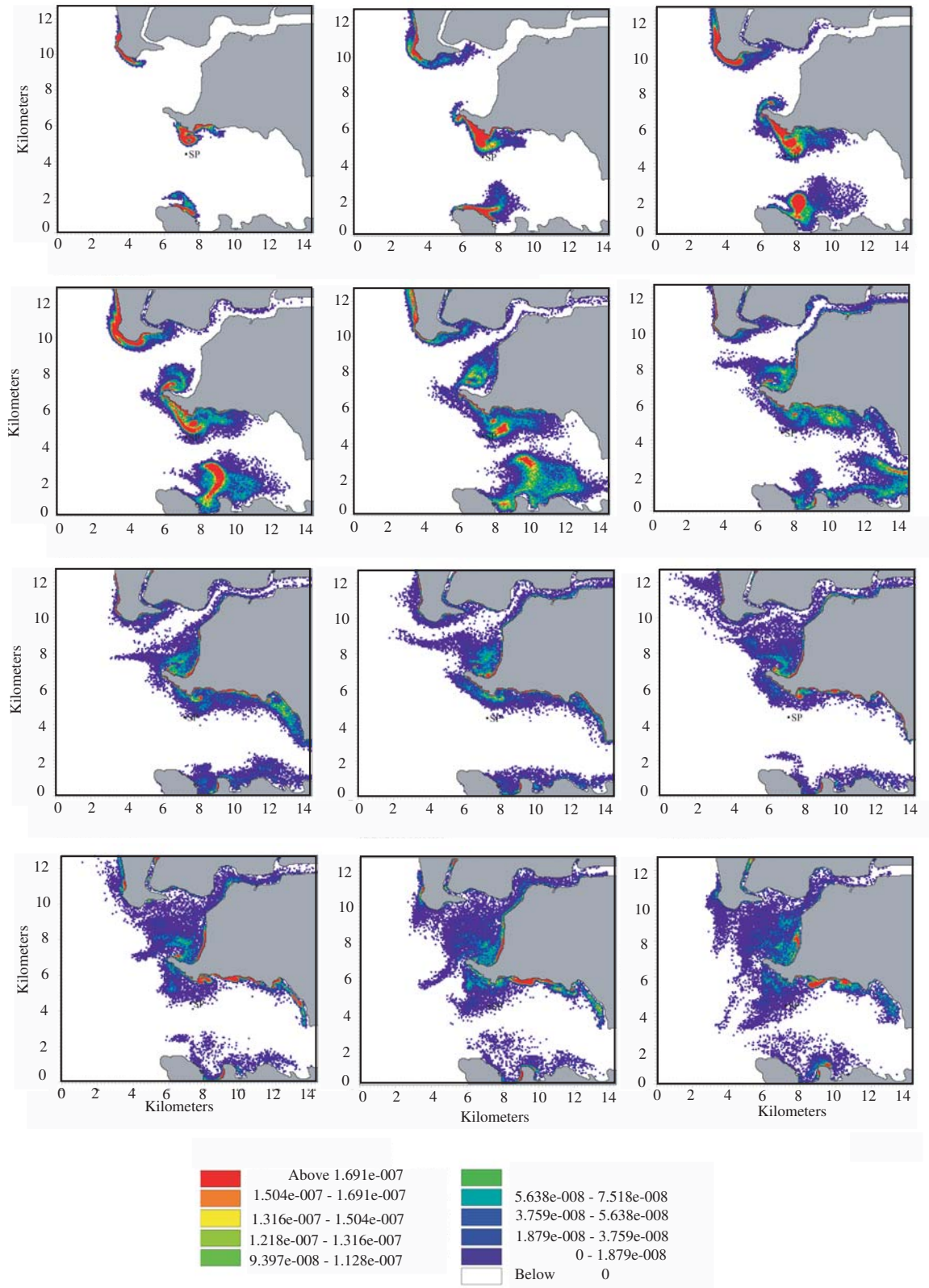


Figure 5.11: Barnacle larval transport during NE monsoon period in Mandovi-Zuari

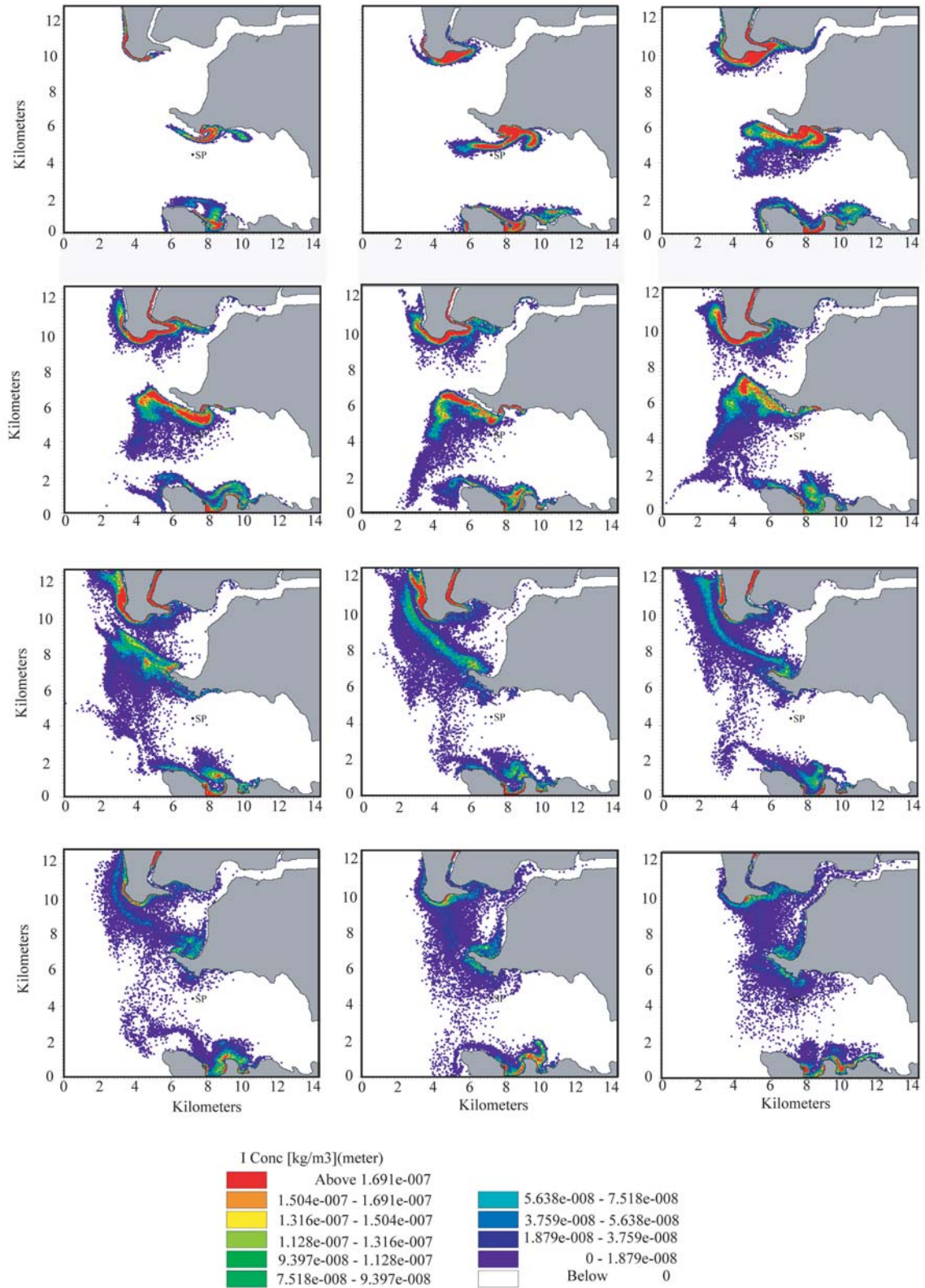


Figure 5.12: Barnacle larval transport during pre monsoon period in Mandovi-Zuari

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.

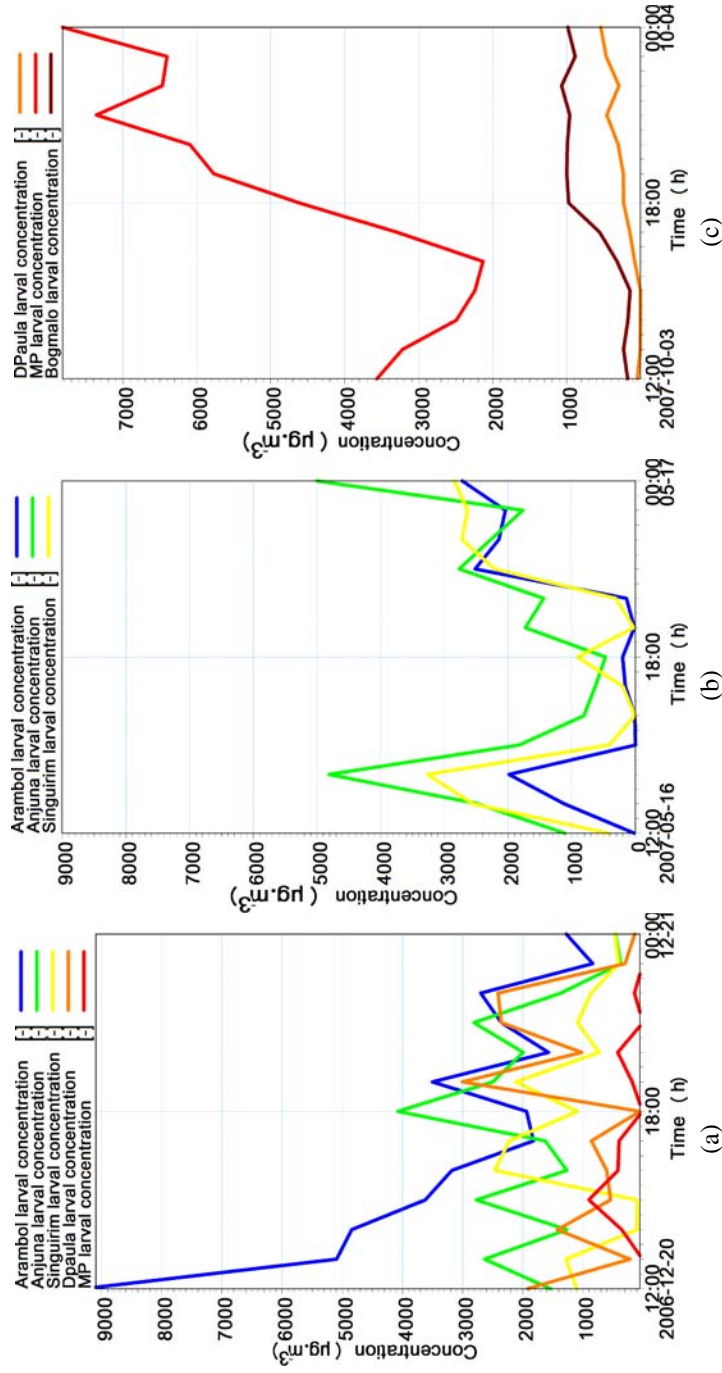


Figure 5.13: Quantum of larvae reaching the sampling point inside the estuary from major spawning sites during (a) December, (b) May (c) October

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

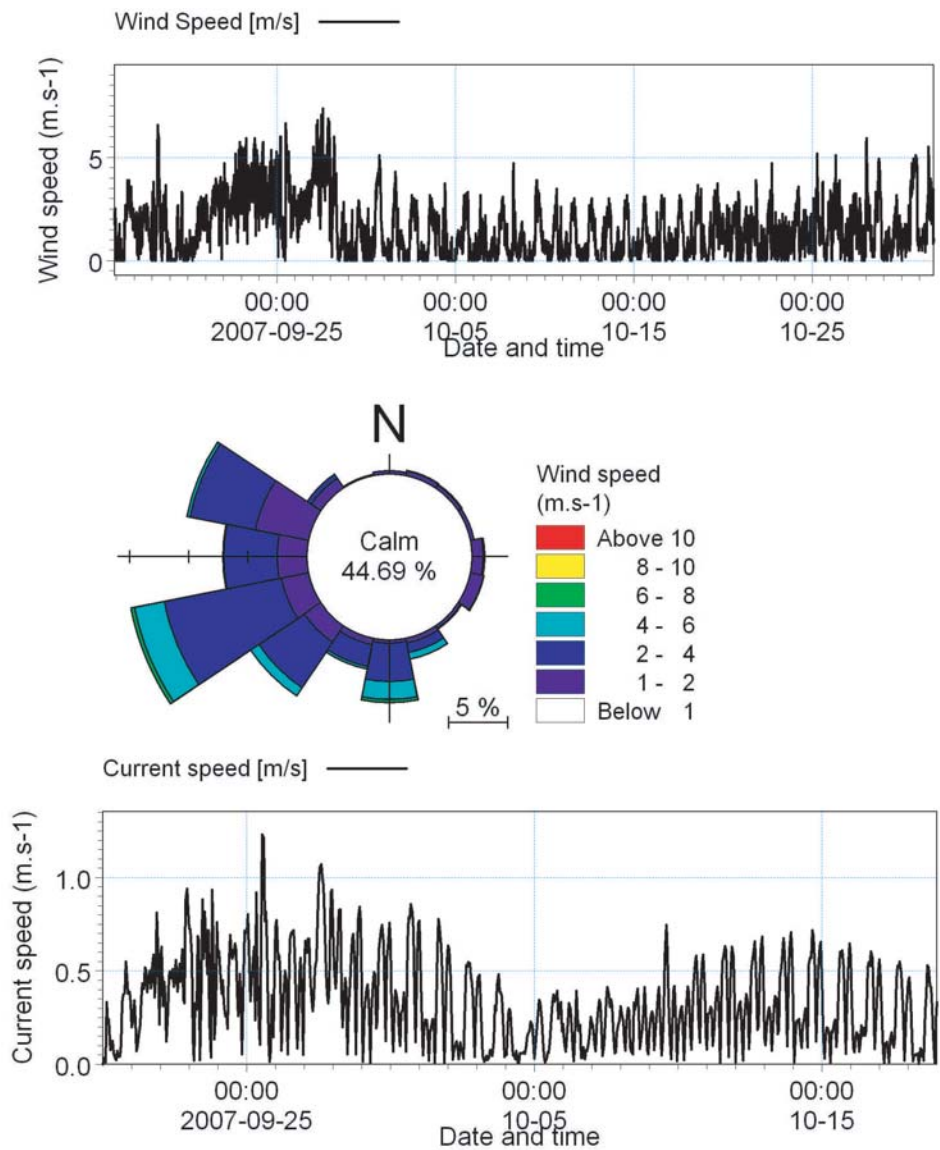


Figure 5.14: Prominent wind and current direction during the unprecedented larval abundance during pre monsoon

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 (± 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 merguensis*. 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 penaeid shrimps in the water column. This indicates 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

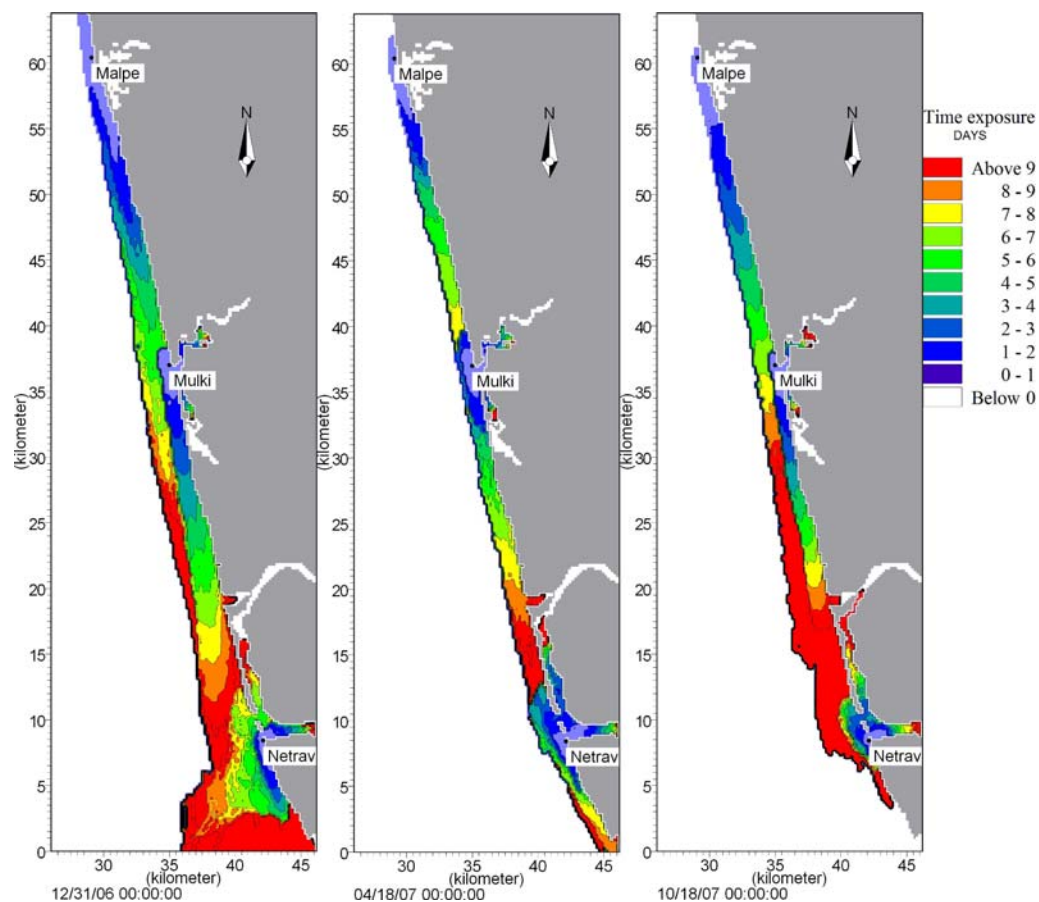


Figure 5.15: Simulation of particle trajectories from three stations along the coastal waters of Mangalore during pre monsoon, post monsoon and NE monsoon

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.