

**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 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.

*Keywords:* Larval retention; dispersal; numerical simulation; tidal currents; eddies; fisheries.

## 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, 1993). The collective contribution of fish production in the GoK during 2007-08 was 18.8% to the total production of Gujarat State. During 2007–2008 total fish landing for Gujarat was  $6.77 \times 10^5$ t, contributing about 22% to the total Indian production of  $30.27 \times 10^5$ 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 and 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 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 Zimmerman, 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. MATERIAL 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 upto 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 and Kankara et al., 2007). The high tidal influx covers vast low lying areas of about 1500 km<sup>2</sup>, 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  $\mu\text{m}$  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 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  $\text{cm}^2$ ) 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, 2005; Babu et al., 2005 and 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, 2000; 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 ( $38 \text{ m}^{1/3} \text{ s}^{-1}$ ) and horizontal eddy viscosity ( $0.5 \text{ m}^2 \text{ s}^{-1}$ ). 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 weight (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 selected 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 to 1.4 cm/s (Lies 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) was simulated 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.

### 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*,  $\overline{me} = \frac{1}{N} \sum_{i=1}^N me_i$ ; *bias* =  $\overline{diff} = \frac{1}{N} \sum_{i=1}^N dif_i$ ;

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

### 2.5 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. 3 a). The modelled u and v current components are also similar to the measured current components (Fig. 3 b & c). Correlation coefficients of 0.59 and 0.54 have been calculated between measured and modelled ebb and flood velocities, 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. The RMS is not corrected for the bias and difficult to be interpreted unless the bias is significant. The modelled and predicted

water levels show very good agreement with no phase difference. 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. Seasonal changes in the flow patterns in the Gulf were simulated (Table 3) for three different 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 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).

### **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) 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 (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 ( $340^{\circ}$ ) (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 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  $\geq 30\%$  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 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 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 never migrating more than short distances. 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 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 (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 & 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 ichthyoplankton will be a better fisheries management strategy for the gulf, imbibing the concepts of an ecosystem-based spatially structured approach (Richardson et al., 2010).

#### **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 ( $\geq 30\%$ ) 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.

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### **Author disclosure statement**

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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        |



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

| Parameters            |       | Mean | Bias | RMS  | Correlation coefficient | <i>No. of time steps</i> |
|-----------------------|-------|------|------|------|-------------------------|--------------------------|
| 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 minutes 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   |

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

| Site |               | Egg abundance<br>(number/100m <sup>3</sup> ) |             | Site features   | Geographical barrier   | Fishing activity   |
|------|---------------|--|-------------|---|--|--|
|      |               | April<br>2002                                | Nov<br>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 7.31m 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 |

## Figure legends

Fig.1. Gulf of Kachchh and its topographic features

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

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

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

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

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)

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

Fig1

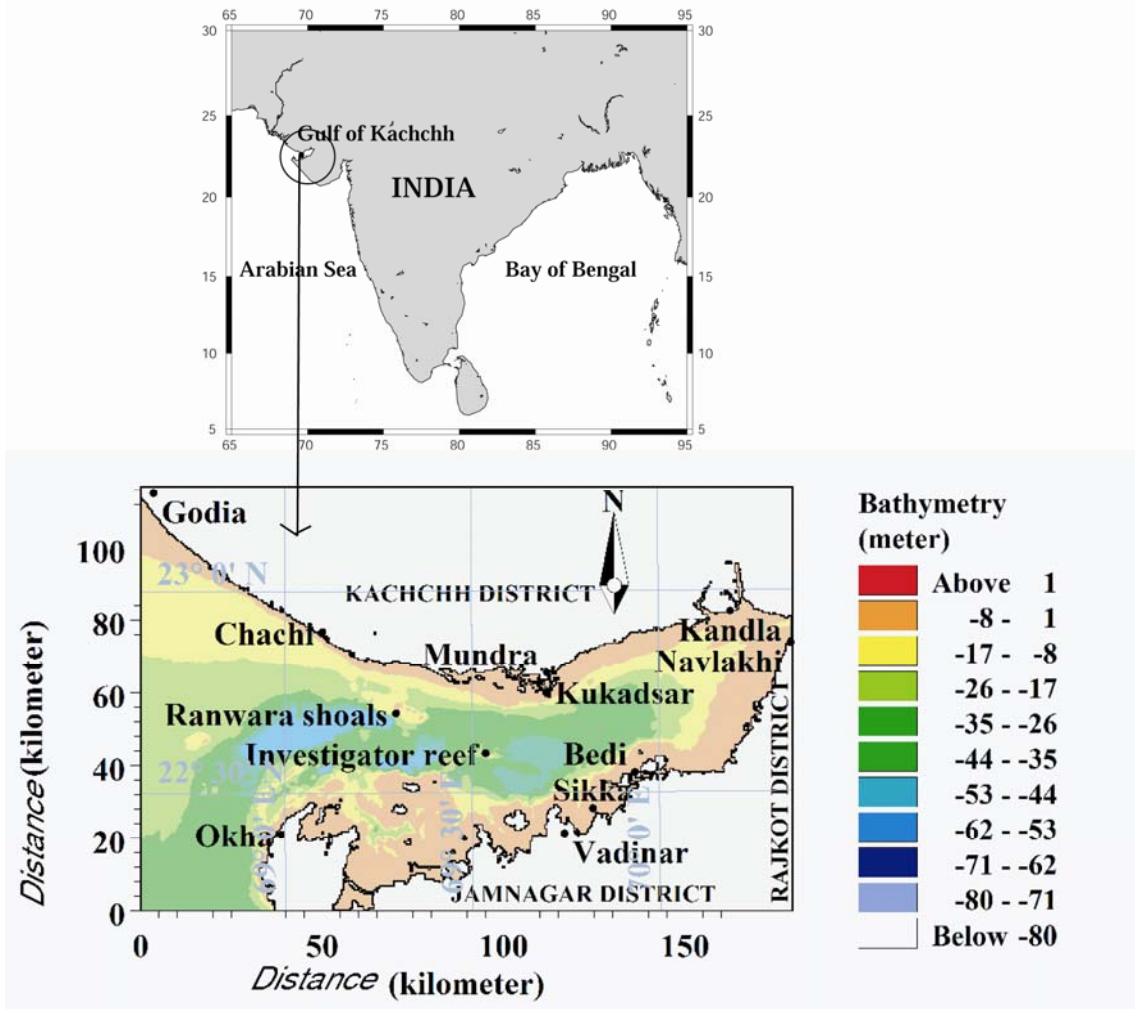


Fig2

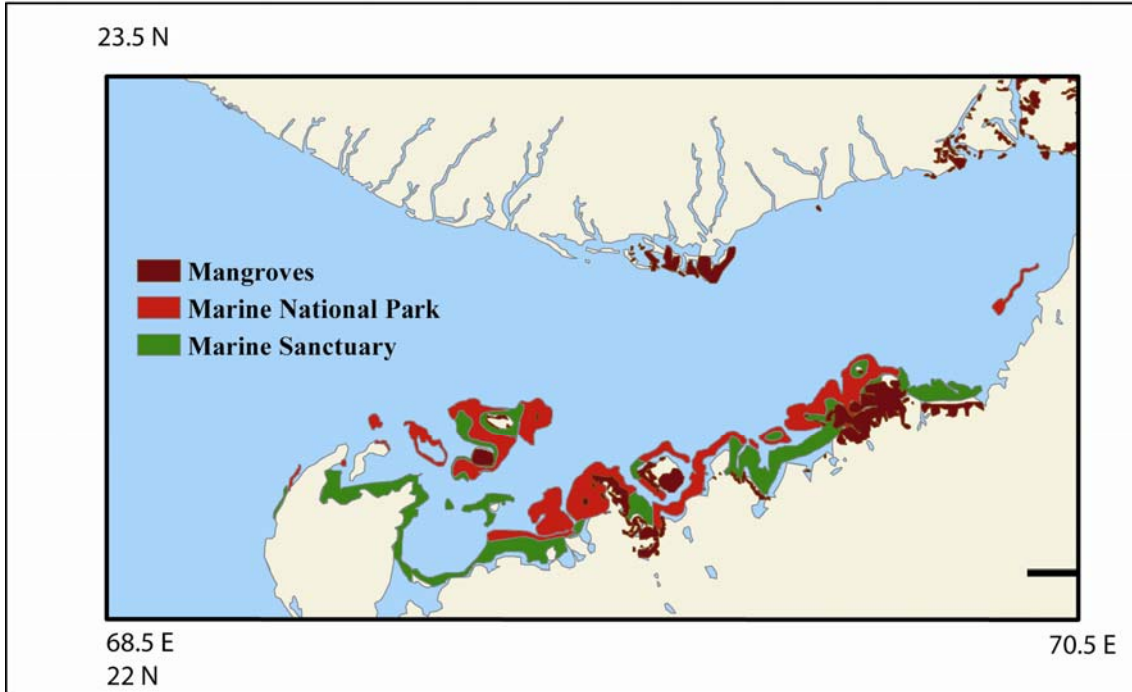


Fig 3

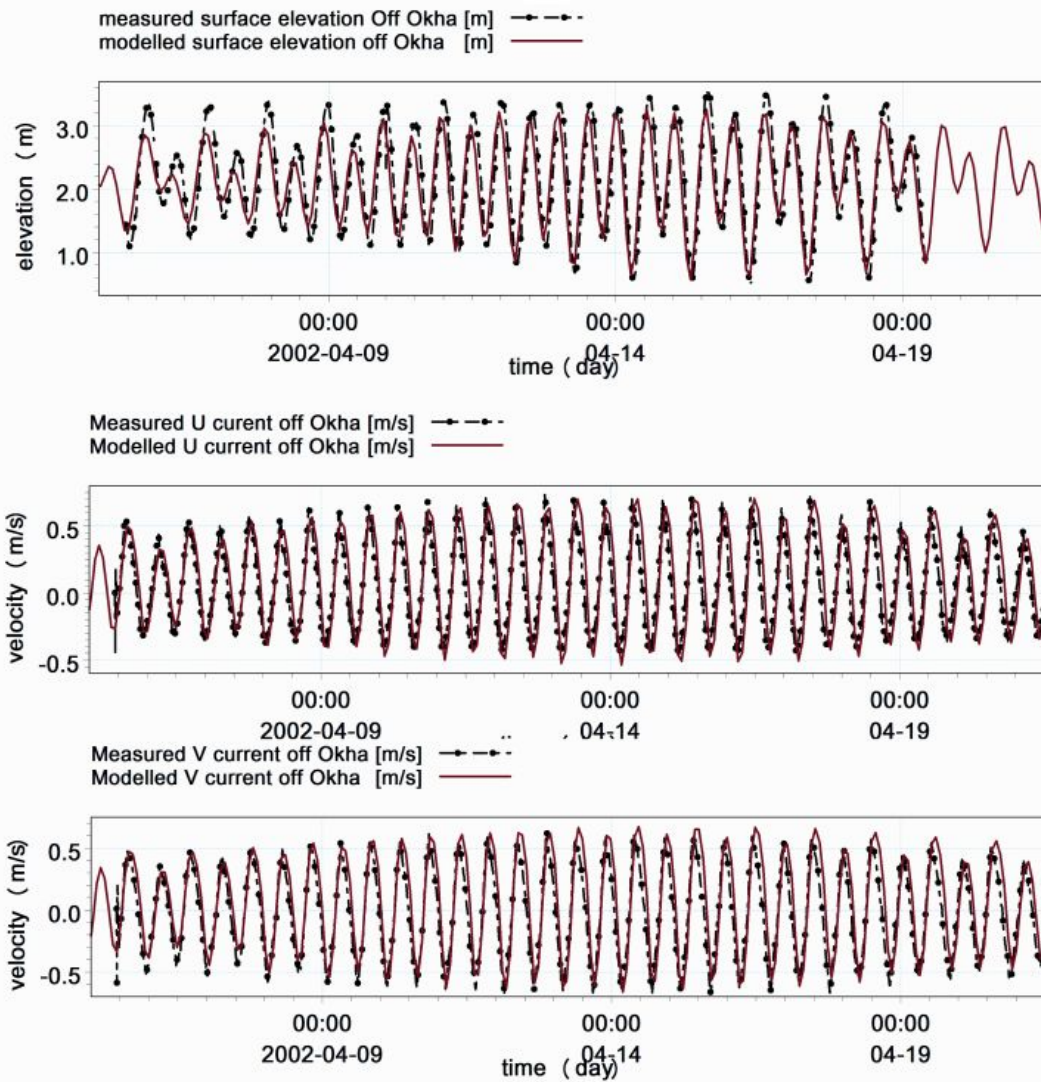


Fig 4

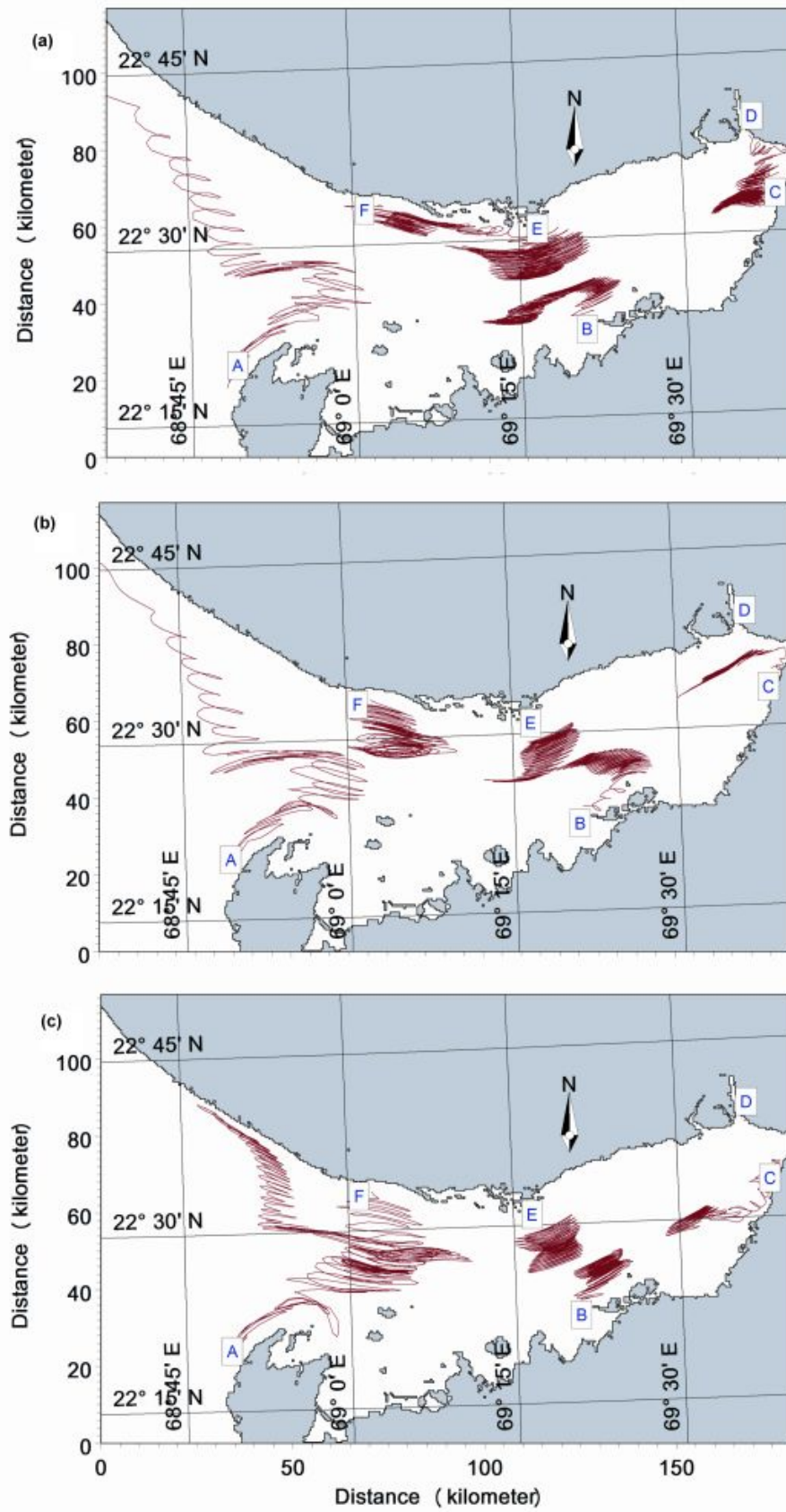




Fig5

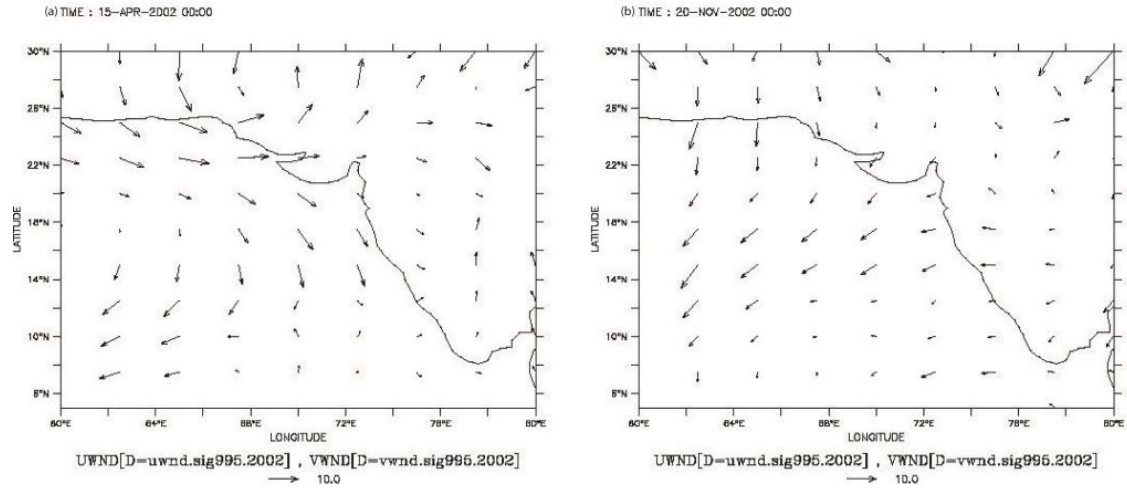


Fig6

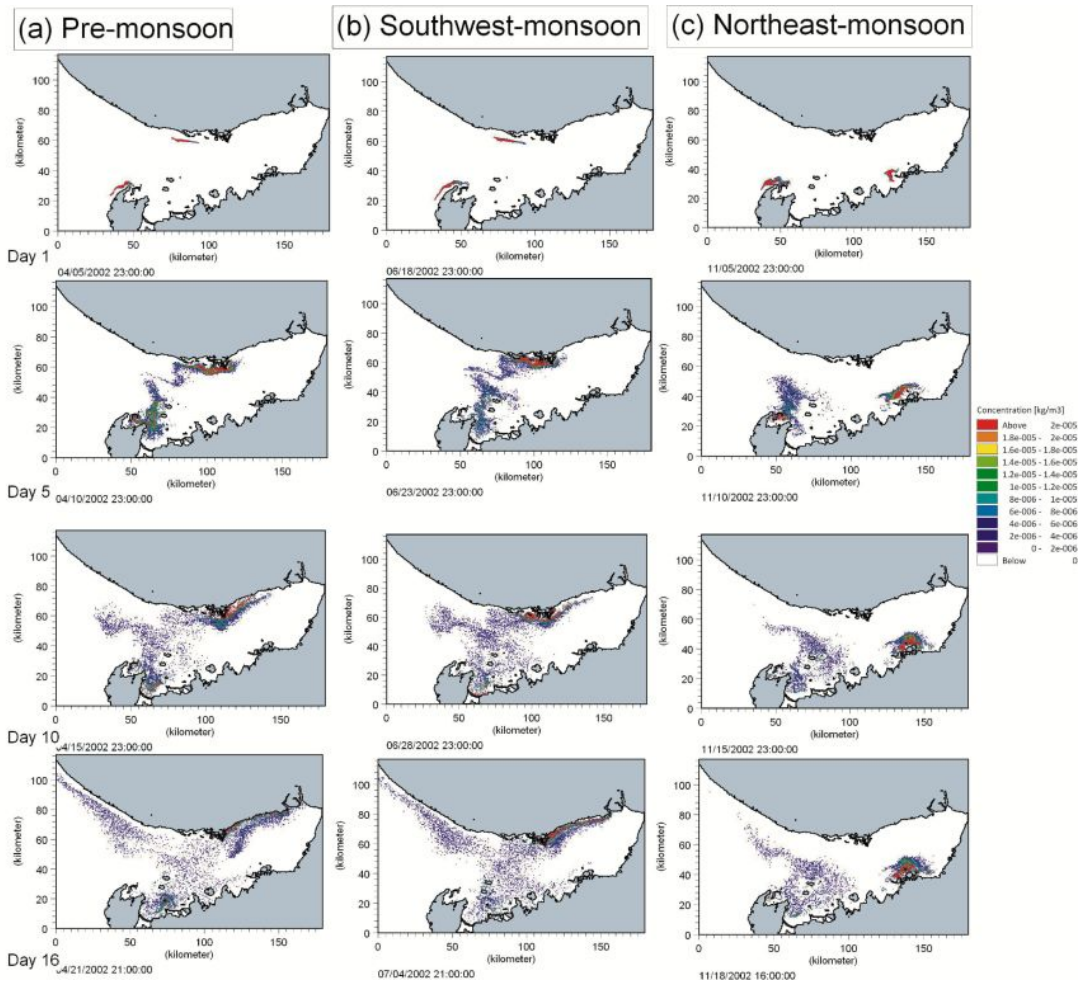


Fig7

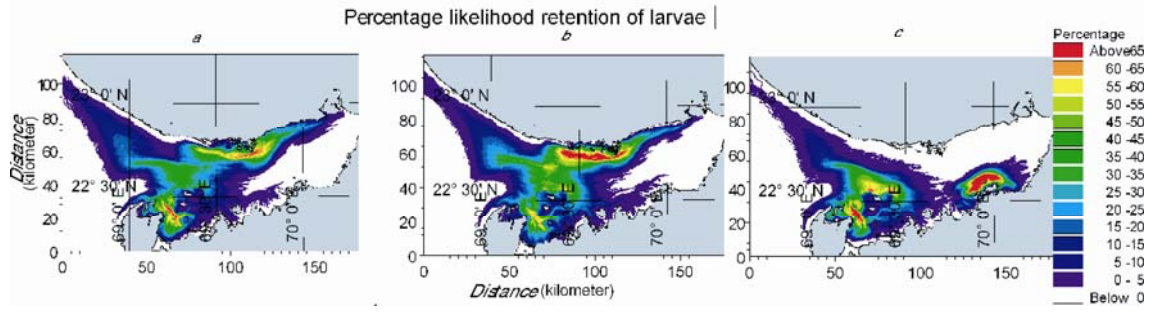


Fig8

