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Barnacle larval transport in the Mandovi-Zuari estuarine system, central west coast of India

(Running title: Barnacle larval transport in an estuarine system)

Grinson George*, Dattesh .V. Desai, Chetan A. Gaonkar., V. M. Aboobacker, P. Vethamony, and

Arga Chandrashekar Anil

National Institute of Oceanography, Council of Scientific & Industrial Research, Goa

*Central Marine Fisheries Research Institute, Indian Council of Agricultural Research, Kochi,

Corresponding author e-mail: grinsongeorge@yahoo.co.in

Abstract

A two dimensional hydrodynamic and particle tracking model was used to estimate the dispersion and retention of barnacle larvae from their possible spawning sites in a tropical monsoon influenced estuarine system (central west coast of India). Validation of the hydrodynamic simulations yielded good match with field measurements. The pattern of larval dispersal in the region varied with the winds and currents. The seasonal changes in abundance could be attributed to physical forcing and weather conditions. The extent of barnacle larval dispersal from spawning sites varied from 10 to 78 km for different sites and seasons. During a 24 hour cycle, the larval abundance showed one to two peaks in the estuarine area. The increased larval abundance is favored by the flood currents, pushing the larvae into the estuary. Physical forcing in the region helps in transport of the larvae from their spawning sites hugging to the coast and contributing to the population within the estuary. Field observations and numerical experiments suggest occurrence of higher larval abundance in the estuary during post-monsoon. The dispersal pattern indicated that the barnacle population present in the estuary is well-mixed with a seasonally changing pattern.

Keywords: Numerical modelling; Barnacle larvae; Hydrodynamics; Estuary; Dispersion and retention.

1. INTRODUCTION

Mandovi-Zuari is one of the major estuarine systems of the central west coast of India. Barnacles are found in large numbers in the intertidal areas along the boundaries of this estuary and biofouling by barnacles poses a major threat to navigation, fishing, tourism and port related activities in this estuarine system (Desai and Anil 2005; Desai et al, 2006). *Balanus amphitrite* Darwin, is a dominant intertidal and fouling barnacle in the Mandovi-Zuari estuarine systems (Anil 1986; Desai and Anil 2005). 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 (Anil and Kurian, 1996; Anil et al., 2001; Desai and Anil, 2004) The PLD phase of barnacle is 6-10 days and on completion of their PLD phase (6–10 days), the larvae settle down if a suitable hard substratum is available or else they will continue their PLD phase in search of a viable substratum and finally perish if they fail to settle on a hard substratum (Gaines and Bertness, 1992; Seed and Suchanek, 1992). A characterization based on the quantity of food, temperature, salinity, dissolved oxygen etc during planktonic life indicates the approximate duration of planktonic larval life (Anil and Kurian 1996; Anil et al. 2001; Desai and Anil 2004; Desai and Prakash 2009).

A sufficient retention time in an estuarine basin could trap larvae (Lobel and Robinson 1986), Zooplankton (Boicourt 1982; Sammarco and Andrews 1988, Murdoch 1989; Thiebaut et al. 1994), phytoplankton (Roff et al. 1979) or neutrally buoyant material (Wolanski and Hamner 1988; Black et al. 1990). Pelagic larval phase of barnacle is responsible for their dispersion or retention, because during this phase the hydrodynamic forcing on the larvae exceeds its swimming ability (Chia et al. 1984; James et al. 2002; Cowen et al. 2006; Aiken et al. 2007). Thus, 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. salinity and temperature) or biological (e.g. availability and quality of sestonic food or predation) factors are imperative in their survival and influence the length of the larval life. The dispersion of larvae critically depends 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 turbulent diffusion, tides, storm-mixing events and wind driven currents, internal waves, meso-scale eddies and large scale general circulation (Okubo 1994). The circulation pattern in the north Indian Ocean is influenced by seasonally reversing monsoon winds (Shetye et al. 1991). Transfer of water masses between the Bay of Bengal and the Arabian Sea ensues due to eastward summer monsoon current (SMC) during

southwest (SW) monsoon and westward winter monsoon current (WMC) during northeast (NE) monsoon (Shankar et al. 2001). Currents along the west coast of India are dominated by tides, which are mixed with dominant semi-diurnal constituents (Unnikrishnan et al. 1999). Tidal range increases from south to north due to broadening of the continental shelf (Kunte et al. 2000).

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 pattern (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 movement landward and surface water seaward when averaged over a number of tides.

Larval longevity and water movement establish the potential for dispersal, whereas larval behavior 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 (Kinlan and Gaines 2003; Kinlan et al. 2005; Palumbi 2003). This is in agreement with oceanic diffusion measurements and suggests a positive correlation between time and spread. It has been indicated that several hours of larval period result in a 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 (Shanks 2009). Significantly greater dispersal requires a substantially longer pelagic period.

In the present work, we studied larval retention and dispersal at the confluence of estuary with sea. This study is motivated by the member-vagrant hypothesis that the larval dispersion and retention pattern in the region is 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 the manifestation of a closed group trapped by the hydrodynamic or geographical limitation. 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 dispersion processes.

Utilization of high resolution biophysical models to estimate dispersal distance or retention is advantageous as the models allow multiple releases of virtual larvae, thus making each individual simulation equivalent to an isolated measurement of dispersal event. These simulations provide opportunities for repeated experiments through time and space on expected variability in hydrodynamics and allow construction of a connectivity matrix (Cowen and Sponaugle 2009). The scale and predictability of larval dispersion and retention remains unknown largely due to the difficulty in measuring larval dispersion in open estuarine environments. Numerical modelling provides a solution for this as the hydrodynamics and particle transport could be simulated to near real values for a large domain at fine resolutions, enabling us to have more experiments on larval dispersion and retention in open estuarine environments. We validated the modelled larval dispersion using field data. We have identified suitable time and location for larval dispersal and settlement, and accordingly calculated the maximum and minimum distance the larvae can disperse in different seasons.

2. MATERIAL AND METHODS

2.1. Study area and model domain: The study region (Dona Paula bay in the Zuari estuary, 15° 26' 18.44" N and 73° 47' 53.9"E) is located along the central west coast of India. Fig.1 shows the study area and model domains. Model domains were set up with coarse and fine resolution rectangular Cartesian grids of 500 m×500 m and 50 m x 50 m spacing, respectively. Bathymetry data obtained from MIKE-CMAP and Naval Hydrographic Office (NHO) chart 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. The main purpose of this modelling is to study the larval dispersion along the open coast. However, this coarse domain is inadequate to resolve some specific details at certain areas, especially in the estuary. Hence, a fine resolution domain, which extends 13 km and 14 km in X and Y directions, respectively, has been considered within the larger domain to simulate hydrodynamics and larval transport in the study region.

2.2. Hydrodynamic modelling: Few models have exposed the hydrodynamics of these areas. Shetye and Murty (1987) used a one-dimensional numerical model to study the annual salt budget in the Zuari. Shetye et al. (1995) found that the momentum balance in these estuaries is primarily between pressure gradient and friction. Unnikrishnan et al. (1997) developed a 1D network numerical model for the entire estuarine system including all the tributaries to study the decay of the tidal elevation in

the upstream regions of these estuaries during the monsoon season. The mean downstream velocity associated with freshwater influx is sufficiently large to prevent upstream propagation of tides, thereby causing the decay. As the maximum depth of the coastal region considered in the model is less than 15 m, we have used a 2D model.

In order to simulate the tidal elevations and flows at the study area, a depth averaged two-dimensional hydrodynamic model, MIKE 21 HD, developed by DHI Water & Environment, Denmark has been used (DHI, 2001). Surface elevation and current velocities are calculated by solving dynamic and vertical integrated equations of continuity and conservation of momentum in X and Y directions. This model has been used earlier to study the flow characteristics at various coastal and estuarine regions (Babu et al. 2005; Chubarenko and Tchepikova 2001).

There are three open boundaries for the coarse model domain: west boundary is between Karwar and Vengurla, south boundary is perpendicular to Karwar and north boundary is perpendicular to Vengurla. The tidal elevation measurements carried out for the above period were not sufficient to force the model at open boundary for a longer period. In order to force the model at the open boundary for a longer period, the amplitude and phase of major tidal constituents were derived. The tidal range in the Mandovi and Zuari estuaries is about 2.0 m. M2 (Principal lunar semi-diurnal constituent) is the dominant constituent in these estuaries. The amplitude of M2 is about 55 cm, which is three times higher than the S2 (Principal solar semidiurnal constituent). The dominant diurnal constituents are K1 (Luni-solar declinational) and O1 (Lunar declinational) (Manoj et al. 2009). Tidal elevations at Karwar and Vengurla have been predicted using these tidal constituents provided by the International Hydrographic Bureau, Spec. Pub, Monaco (Anonymous 1930) and applied at the south and north boundaries, respectively. The tidal elevations between Karwar and Vengurla are linearly interpolated to each grid of the west boundary.

Tidal elevations and fluxes from coarse model were extracted at the boundaries of the fine resolution model domain and applied as boundary conditions to simulate the tidal elevations and flows in the fine resolution model domain. In both coarse and fine model domain, apart from the tides, wind data measured at Dona Paula (Goa) coastal station using Automatic Weather Station (AWS) were also applied as input for the simulations. Wind data measured at 43.5 m height were reduced to 10 m height using the power law- a method for extrapolating the wind speeds between two heights (Peterson and Hennessey 1978). Winds are assumed to be uniform over the whole domain. As winds such as NCEP are in coarse grid ($2.5^{\circ} \times 2.5^{\circ}$), AWS winds were applied over the entire model domain.

During model simulation, the time step interval for the simulation has been selected in such a way that it should satisfy the stability criterion. Time steps of 20 s and 15 s were considered in the coarse model and fine model, respectively. The corresponding Courant numbers are 1.7 and 3.6, respectively. The calibration parameters applied in the simulations after tuning the model are eddy viscosity, bed resistance and wind friction factor. A velocity-based Smagorinsky scheme (C_s), with a constant value of $0.5 \text{ m}^2 \text{ s}^{-1}$ has been applied to calculate the eddy viscosity. A Manning number of $32 \text{ m}^{1/3} \text{ s}^{-1}$ has been considered as the calibration parameter for the bed resistance. The wind friction factor is taken as 0.0026.

The simulated tidal elevations and current velocities have been validated with predicted tidal elevations and measured currents (RCM mooring location is marked in Fig.1b). The mooring depth is 6 m. Currents are measured for every 10 minutes interval using Recording Current Meter (model: RCM7; make: Aanderaa, Norway) during 14 November – 10 December, 2007. The current speed and direction was resolved into u 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. Calibration problems were observed while matching the simulation results along the narrow channel, where the flow speed is difficult to achieve in comparison to the mouth of the estuary, with the measurements. This problem was overcome by applying friction factors to the model, and the model was calibrated with observed currents at one location. This calibrated model has been used to simulate flow patterns during three different periods: December 2006, May 2007 and October 2007.

2.3. Larval transport modelling: The particle analysis (PA) module of the MIKE 21 (DHI 2001) has been used to simulate the larval transport. 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. Hydrodynamic modelling (HD module) is the basic requirement for the larval transport modelling (PA module). The PA module takes the input from the HD module. It uses the Lagrangian random-walk technique to track the movement of the particles released, and the same can be effectively utilized for tracking the retention or dispersion of hypothetical larvae released within the domain (Stephens et al. 2006, George et al. 2011, Chetan et al. 2012).

In the present study, for the simulation of barnacle larval transport, the following assumptions/factors were imposed:

- i. Period of simulation: based on the previous studies on barnacle in the same region, the PLD phase is approximated as 10 days for the present study, and after which they are treated as

settled (Anil and Kurian 1996; Anil et al. 2001; Desai and Anil 2004; Desai and Prakash 2009).

- ii. Total particles released: one particle is assumed to be equivalent to 1000 larvae as it is difficult to model larval transport with a large number of particles. At each time step, 4000 larvae were released making it into 11.92 million hypothetical larvae over 2980 time steps (with a time step interval of 30 s).
- iii. Particle size of released larvae: release is continued for 24 hours and 50 minutes covering 2 tidal cycles as the source flux. Assuming a mass of 5 μg for each larva, 0.2 mg of larvae per second was released in each time step. The estimated time of hatch was controlled using a uniform source flux defining the mass and release of larvae.
- iv. The simulations have been carried out for 15 days duration in each of the season, considering the release of larvae on 6th day and observed the larval transport for next 9 days after the release. Larvae are defined as neutrally buoyant, and they follow the prevailing flow without being settled.
- v. Dispersion of the larvae has been analyzed for each season. The dispersal pattern at the beginning (after complete release of larvae), 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 has also been extracted at various sampling stations to assess the intensity of retention or dispersal under the influence of flow and associated dispersion processes.
- vi. The larval abundance in a region is affected by predation, mortality and behaviour (Fiksen et al 2007). 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. Turbulent tidal transport has no effect on barnacle nauplii and cyprids compared to larval forms of mollusks (veligers) (Jessopp 2007). Particles that reach the open boundaries or hit land before the end of the 10 days get deducted from the model domain.
- vii. The larvae have been released based on the nature of site as barnacle spawning takes place only in rocky areas and areas with a hard substratum.

2.4. Spawning sites: The spawning sites for larval release were selected on the basis of an exploratory survey conducted in the study site. The spawning sites are Vengurla, Arambol, Anjuna, Singuirim, Dona Paula, MPT (Mormugao Port), Bogmalo and Galgibagh (Fig.1a). The spawning

sites were selected based on visual observations on the occurrence of barnacles in the intertidal rocky habitat and they represented the spawning areas.

2.5. Larval sampling: Larval samples were collected from the sampling point near Dona Paula (Fig.1a) on hourly basis for a period of 24 hours during 3 different sampling periods (December '06, May '07 and October '07), representatives of 3 different seasons namely NE monsoon, pre-monsoon and post monsoon. A detailed explanation about the seasons has been provided in section 3.3.1 to 3.3.3. The October 2007 (post monsoon) field sampling was carried out in the beginning of the month during which the reversal of the monsoonal wind occurs.

Samples were collected using Haron-Trantor net of mesh size 100 μ m. 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.

2.6. Data Analysis: Data of barnacles which were collected during different months were log-transformed to ensure normality of means and homogeneity of variances before subjecting to statistical analysis. The log-transformed data was then subjected to two-way analysis of variance (ANOVA) to evaluate the variance in larval abundance during different sampling hours, and tidal height.

3. RESULTS

3.1. Field observation of larval abundance: Larval abundance was highest during October '07 (Fig. 2). The abundance significantly differed between all the three sampling periods (ANOVA: $p \leq 0.0005$). There was an hourly variation in the larval abundance during May '07 and October '07 sampling. During December '06 sampling, larval abundance peaked between 2330 to 0230 hours with a non-significant variation between different sampling hours (ANOVA: $p \geq 0.05$). During May '07 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 '07 sampling, two peaks in larval abundance were observed during 1730 and 0130 hours.. Analysis of variance also showed a significant variation between different sampling hours (ANOVA: $p \leq 0.05$) during this sampling period. The number of cyprids in the study region was less compared to the nauplii.

3.2. Hydrodynamics of the study region: Model results have been validated with measurements carried out during 14 November – 10 December 2007 (Figs. 3a, b and c). The modelled u and v-velocities show good match with the measured current velocities (Figs. 3a and b). The modelled and predicted tidal elevations (Fig. 3c) show good match with no phase difference. 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. The modelled v-velocity is slightly under-estimated, with a bias of -0.06 m/s. The Root Mean Square error calculated for u and v velocities are 0.37 m/s and 0.14 m/s, respectively.

The coastal circulation indicates that 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 estuary, the flow is towards east while flooding and towards west while ebbing. The tidal currents play a major role in the cross-shore movement of the particles in the estuarine system. However, small scale tidal eddies also influence the dispersion characteristics inside the estuaries. The flow is relatively stronger inside the Mandovi River. The maximum current speeds in the study area during flooding are 0.96, 0.88 and 0.70 m/s during pre-monsoon, post-monsoon and northeast (NE) monsoon seasons, respectively, whereas they are 0.89, 1.08 and 0.65 m/s, 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 m/s during pre-monsoon, post-monsoon and NE monsoon seasons, respectively, whereas they are 0.33, 0.39 and 0.20 m/s respectively, while ebbing. Currents in the estuary tend to disperse the larvae, but features like eddies and geographical limitations tend to retain them.

3.3. Larval dispersion and retention as envisaged in the numerical simulation: The results of simulation carried out in the large domain were analysed for assessing the larval dispersion from the possible spawning locations and calculating the number of larvae reaching the sampling point. The extent of larval dispersion is influenced by winds, tides and currents of the respective season as described below. This could be the reason for the low larval abundance in the Zuari estuary during this season. The larvae released by local population (Dona Paula and Mormugao spawning grounds) only were retained at the field sampling site.

3.3.1. NE Monsoon season: Though tide generated currents are dominant, NE winds do have a role in the larval transport during December. A net southward flow along the coast has been simulated for the particle transport from all the spawning locations (Fig. 4). However, the quantum of particles

reaching the sampling point, which is same as the station used for field sampling at Zuari estuary, is in the decreasing order from Arambol to MPT. No particles released at the locations further south of MPT, reached the sampling point in the Zuari estuary. This also coincides with low larval abundance in the Zuari estuary. We observed a net off-shore particle transport off Singuirim and Dona Paula due to NE winds supported with tidal currents. For the spawning locations south of Singuirim, major amount of particles aggregated along the coastal belt south of Bogmalo.

3.3.2. Pre-monsoon season: 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. This results in a frequent and intense movement of particles in the southward direction and hence, the spread of the particle 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 (Table 1). 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. There is no effect in the sampling point at Zuari estuary for the particles released at other locations.

3.3.3. Post-monsoon season: During the first half of October, there exists southwest (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 northwards. The field sampling and simulations took place during the first half of October during which the reversal of the monsoonal wind occurs. The effect of retrieval of monsoon is a gradual process and the selected time period illustrates the same. Therefore, in October dispersal of particle occurs northwards predominantly (Fig. 6). The particles reaching inside the Zuari estuary is less in the post-monsoon season than in other seasons, and accumulation is near the mouth of the estuarine system. The quantum of particles reaching the sampling point at Zuari estuary is in the increasing order from spawning locations at MPT, Bogmalo and Dona Paula and this was observed by higher larval abundance at the field sampling site and the larval abundance is at its peak during this season compared to other seasons.

There is spatial and temporal variation in the larval dispersal pattern from different spawning sites. The coastal waters of the study area vividly indicate that northern spawning sites are contributing to larval abundance in the estuary during December and May. But, with the reversing wind and current

patterns in October, the larval abundance inside the estuary is contributed by southern spawning sites (Table 1).

3.4. Modelled and observed barnacle larval retention

The results of the larval dispersion simulation carried out in the fine resolution domain (Figs. 7, 8, and 9) indicate least retention of larvae in the estuary during pre-monsoon period. This is in concurrence with the observed field data too (Fig. 2). There is higher abundance of larvae inside the estuary during post-monsoon followed by NE monsoon seasons. The larval movement is supported by the ebb and flood (Fig. 2). But higher larval abundance is noticed during the field measurements during post-monsoon. Less retention of larvae has been observed in the Zuari estuary and the larvae released from spawning sites were transported towards the Mandovi estuary during NE monsoon and post-monsoon, as envisaged from the simulations. This could be reason for higher larval abundance between two high tides as larvae are retained within the estuary.

4. DISCUSSION

Barnacles 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 indicate 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 for December, May and October (Figs. 7, 8, and 9) are consistent with the field observations (Fig. 2), but October month showed high field values. The quantum of larvae reaching the estuary in the model results during the field sampling dates (Fig. 10 a,b,c) indicate 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 to their transport.

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 is protracted over the entire year with a lull during SW-monsoon season however the maximum larval abundance was observed during September to November. This was observed in the spawning area where a dominant barnacle *Balanus amphitrite* inhabit (Desai and Anil 2005; Desai et al 2006). With several spawning sites of barnacles existing in the study area, input of nauplii from the gravid individuals from all the spawning sites will have an impact on the settlement and recruitment of new population. However, there is no distinct pattern of spawning over an annual cycle. Maximum percentage of barnacles, *Balanus amphitrite* with ripe ovaries were observed during post-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 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 AWS field measurements and hydrodynamic model results in the study region during October indicate favorable wind and current patterns corroborating the view that more barnacle larvae are transported to the estuary from the southern sites (Fig. 11).

The release of larvae mostly coincides with high tide, and newly released nauplii and subsequent stages depend on flow of water. The modelled (Figs. 7, 8, and 9) and observed pattern of larval dispersion (Fig. 2) 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 site near Dona Paula during October. The abundance is comparatively less in May than December with a wider dispersal pattern. But for October, a sampling away from the dispersal core reflects a lesser abundance as the larvae may not be spreading up to that 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 explains the possible transport of larvae (Table 1) 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).

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 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 field sampling of barnacle larvae outside the estuarine domain clearly indicated a less abundance of larvae. The samples were collected from off Goa (15°26', 73°44') during 4 March 2005, 10 October 2005 and 16 January 2006. The methods followed for the collection of samples were similar as given in section 2.5. in materials and methods. The average abundance of larvae which was collected from offshore domain during 3 different sampling periods was 474 (± 664) larvae per 100 m³, which is much lower than the larval abundance within the estuary. Alvarez et al. (1990) illustrated through their study that along-shore advection was on an average ten times stronger than the cross-shore advection. 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 advection (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 lived larvae (Olson 1985; Pineda 2000).

5. CONCLUSIONS

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 supply barnacle larvae to the estuary during all seasons except post-monsoon. The barnacle larval population in the estuary is well mixed with spawning sites located north and south of the estuary contributing to the larval abundance. Larvae traverse as far as 78 km along the coastal waters with a minimum dispersal of 3-5 km.

Barnacle larval abundance is higher during post-monsoon as large quantities of larvae are supplied from spawning sites located south of the estuary. This is further strengthened by high flood currents. Unlike a pelagic open offshore larval pool for barnacles in Californian coast (Pineda, 2000), the acorn barnacle larvae are concentrated only in the near-shore waters and estuarine mouth as seen in the observations and numerical experiments.

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REFERENCES

- Aiken CM, Navarrete SA, Castillo MI, Castilla JC (2007) Along-shore larval dispersal kernels in a numerical ocean model of the central Chilean coast. *Mar Ecol Prog Ser* 339:13–24
- Alvarez LG, Godinez VM, Lavin MF (1990) Diepersion en la franja costera de Tijuana & Baja California. Near shore dispersion off Tijuana, Baja California. *Ciencias Marinas* (In Spanish and English) 16:87-109
- Anil AC (1986) Studies on marine biofouling in the Zuari estuary (Goa) west coast of India. PhD thesis, University of Karnataka, India
- Anil AC, Dattesh D, Lidita K (2001) Larval development and metamorphosis in *Balanus amphitrite* Darwin (Cirripedia; Thoracica): significance of food concentration, temperature and nucleic acids. *J Exp Mar Biol Ecol* 263:125-141
- Anil AC, Kurian J (1996) Influence of food concentration, temperature and salinity on the larval development of *Balanus amphitrite*. *Mar Biol* 127:115-124
- Anonymous (1930) Tides and harmonic constants. Special Publication No. 26. International Hydrographic Bureau, Monaco, pp.103
- Aparna M, Shetye SR, Shankar D, Shenoj SSC, Mehra P, Desai RGP (2005) Estimating the seaward extent of sea breeze from QuikSCAT scatterometry. *Geophys. Res. Lett.* 32, L13601, doi:10.1029/2005GL023107
- Babu MT, Vethamony P, Desa E (2005) Modelling tide-driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability a marine environmental planning perspective. *Ecol Model* 184:299–312
- Black KP, Gay SL, Andrews JC (1990) Resident times of neutrally buoyant matter such as larvae, sewage or nutrients on coral reefs. *Coral Reefs* 9:105–114

- Boicourt WC (1982) Estuarine larval retention mechanisms on two scales. In: Kennedy VS (ed) Estuarine Comparisons, Academic Press, New York, pp. 445–457
- Chetan A Gaonkar, Samiksha SV, Grinson George, Aboobacker VM, Vethamony P, Arga Chandrashekar Anil (2012) Numerical simulations of barnacle larval dispersion coupled with field observations on larval abundance, settlement and recruitment in a tropical monsoon influenced coastal marine environment. *J Marine Syst* 94:218-231
- Chia FS, Buckland-Nicks J, Young CM (1984) Locomotion of marine invertebrate larvae: a review. *Can J Zool* 62:1205–1222
- Chubarenko IP, Tchepikova I (2001) Modelling of man–made contribution to salinity increase into the Vistula Lagoon (Baltic Sea). *Ecol Model* 138:87–100
- Clancy M, Epifanio CE (1989). Distribution of crab larvae in relation to tidal fronts in Delaware Bay, USA. *Mar Ecol Progs Ser* 57:77-82
- Cowen RK, Paris CB, Srinivasan A (2006) Scales of connectivity in marine populations. *Science* 311:522–527
- Cowen RK, Sponaugle S (2009) Larval dispersal and marine population connectivity. *Ann Rev Mar Sci* 1:443–466
- Desai DV, Anil AC (2004) Impact of food type, temperature and starvation on larval development of *Balanus amphitrite* Darwin (Cirripedia: Thoracica). *J Exp Mar Biol Ecol* 306:113-137
- Desai DV, Anil AC (2005) Recruitment of the barnacle *Balanus amphitrite* in a tropical estuary: implications of environmental perturbation, reproduction and larval ecology. *J Mar Biol Assoc U K* 85:909-920
- Desai DV, Anil AC, Venkat K (2006) Reproduction in *Balanus amphitrite* Darwin (Cirripedia: Thoracica): influence of temperature and food concentration. *Mar Biol* 149:1431-1441
- Desai DV, Prakash S (2009) Physiological responses to hypoxia and anoxia in *Balanus amphitrite* (Cirripedia: Thoracica). *Mar Ecol Prog Ser* 390:157-166
- DHI (2001) User Guide and Reference Manual for MIKE21, Danish Hydraulic Institute, Denmark, pp.90
- Dyer KR (1979) Estuarine hydrography and sedimentation: a handbook. Cambridge University Press, Cambridge, pp. 239
- Epifanio CE (1988) Transport of invertebrate larvae between estuaries and the continental shelf. *Am Fish Soc Symp* 3:104-114
- Fiksen Ø, Jørgensen C, Kristiansen T, Vikebø F, Huse G (2007) Linking behavioural ecology and oceanography: larval behaviour determines growth, mortality and dispersal. *Mar Ecol Prog Ser* Vol. 347: 195–205, 2007.
- Forward RB Jr, Tankersley RA (2001) Selective tidal-stream transport of marine animals. *Ocean Mar Biol Ann Rev* 39:305-353

- Gaines SD, Bertness M (1992) The dynamics of juvenile dispersal: why field ecologists must integrate. *Ecology* 74, 2430–2435.
- George G, Vethamony P, Sudheesh K, Babu MT (2011) Fish larval transport in a macro-tidal regime: Gulf of Kachchh, west coast of India. *Fish Re.* 110:160-169.
- Hughes RN, Griffiths CL (1988) Self-Thinning in barnacles and mussels – the geometry of packing. *Am Nat* 132:484-491
- James MK, Armsworth PR, Mason LB, Bode L (2002) The structure of reef fish meta populations: modelling larval dispersal and retention patterns. In: *Proc Roy Soc London Series*, vol. B 269. Academic Press, New York, pp. 2079–2086
- Jessopp MJ (2007) The quick and the dead: larval mortality due to turbulent tidal transport. *J Mar Biol Assoc U K* 86:675-680
- Kinlan BP, Gaines SD (2003) Propagule dispersal in marine and terrestrial environments: A community perspective. *Ecology* 84:2,007–2,020.
- Kinlan BP, Gaines SD, Lester SE (2005) Propagule dispersal and the scales of marine community process. *Diversity and Distributions* 11:139–148.
- Kunte P, Wagle BC, Yasushio S (2000) Remote assessment of net shore drift along the west coast of India. *PORSEC proceedings* 2:685-689
- Lobel PS, Robinson AR (1986) Transport and entrapment of fish larvae by ocean mesoscale eddies and currents in Hawaiian waters. *Deep-Sea Res* 33:483-500
- Manoj NT, Unnikrishnan AS (2009) Tidal circulation and salinity distribution in the Mandovi and Zuari estuaries: case study. *J Waterw Port Coastal Ocean Eng* 135 (6):278–287
- Murdoch RC (1989) The effects of headland eddy on surface macro-zooplankton assemblages north of Otago Peninsula, New Zealand. *Estuar Coast Shelf S* 29:361–383
- Neetu S, Shetye SR, Chandramohan P. (2006) Impact of sea-breeze on wind-seas off Goa, west coast of India. *J Ear Sys Sci* 115(2):229-234
- Okubo A (1994) The role of diffusion and related physical processes in dispersal and recruitment of marine population. In: *The Bio-physics of marine larval dispersal*, Sammarco PW, Heron ML (eds) vol. 45. Washington, D.C.: American Geophysical Union. pp.5–32
- Olson RR (1985) The consequences of short-distance larval dispersal in a sessile marine invertebrate. *Ecol* 66(1):30-39
- Palumbi SR (2003) Population genetics, demographic connectivity and the design of marine protected areas. *Ecological Applications* 13:S146–S158.
- Peterson EW, Hennessey JP (1978) On the use of power laws for estimates of wind power potential. *J Appl Meteor and Climatol* 17:390-394
- Pineda J (2000) Linking larval settlement to larval transport: assumptions, potentials, and pitfalls. *Oceanogr East Pac* 84-105

- Queiroga H, Cruz T, dos Santos A, Dubert J, González-Gordillo JI, Paula J, Peliz A, Santos AMP (2007) Oceanographic and behavioural processes affecting invertebrate larval dispersal and supply in the western Iberia upwelling ecosystem. *Prog Oceanogr* 74:174-191
- Roff JC, Pett RJ, Rogers GF, Budgell WP (1979) A study of plankton ecology in Chesterfield Inlet, Northwest Territories: an arctic estuary. In: Kennedy VS (ed) *Estuarine perspectives*, 2, Academic Press, New York, pp. 185–197.
- Sammarco PW, Andrews JC (1988) Localized dispersal and recruitment in Great Barrier Reef corals: the Helix experiment. *Science* 239:1422–1424.
- Seed R, Suchanek TH (1992) Population and community ecology of *Mytilus*. In: Gosling, E. (Ed.), *The mussel Mytilus: ecology, physiology, genetics and culture*. Development in Aquaculture and Fisheries Sciences, vol 25. Elsevier, Amsterdam, pp. 87–169.
- Shankar D, Shetye SR (2001) Why is mean sea level along the Indian coast higher in the Bay of Bengal than in the Arabian Sea? *Geophys Res Lett* 28:563–565
- Shanks AL (1995) Mechanisms of cross-shelf dispersal of larval invertebrates and fish. In: McEdward L (ed), *Ecology of Marine Invertebrate Larvae*, CRC, Boca Raton, pp. 323-367
- Shanks AL (2009) Pelagic larval duration and dispersal distance revisited. *Biol Bull* 216:373-385
- Shetye SR, Gouveia AD, Shenoi SSC, Micheal GS, Sundar D, Almeida AM, Santanam K (1991) The coastal current off western India during the northeast monsoon. *Deep Sea Res* 38:1517-1529
- Shetye SR, Gouveia AD, Singbal SY, Naik CG, Sunder D, Michael GS, Nampoothiri G (1995) Propagation of tides in the Mandovi and Zuari Estuarine Network. *P Indian AS-Earth* 104:667-682
- Shetye SR, Murty CS (1987) Seasonal variation of the salinity in Zuari Estuary, Goa, India. *P Indian AS-Earth* 96:249-257
- Stephens SA, Broekhuizen N, Macdiarmid AB, Lundquist CJ, McLeod L, Haskew R (2006) Modelling transport of larval New Zealand abalone (*Haliotis iris*) along an open coast. *Mar Freshwater Res* 57:519–532
- Thiebaut E, Dauvin JC, Lagadeuc Y (1994) Horizontal distribution and retention of *Owenia fusiformis* larvae (Annelida: Polychaeta) in the bay of Seine. *J Mar Biol Assoc U K* 74:129–142
- Unnikrishnan AS, Gouveia AD, Vethamony P (1999) Tidal regime in Gulf of Kachch west coast of India by 2D model. *J Waterw Port Coastal Ocean Eng* 1256:276-284
- Unnikrishnan AS, Shetye SR, Gouveia AD (1997) Tidal propagation in Mandovi and Zuari Estuarine network, West Coast of India: Impact of Fresh water influx. *Estuar Coast Shelf S* 45:737-744.
- Wolanski E, Hamner WM (1988) Topographically controlled fronts in the ocean and their biological influence. *Science* 241:177–181
- Wootton JT (1993) Indirect effects and habitat use in an intertidal community – interaction chains and interaction modifications. *Am Nat* 141:71-89

Legends to figures

Fig. 1 (a) study area showing the large domain with spawning sites and (b) small domain with current meter mooring location and major sites discussed in the text.

Fig. 2 Barnacle larval abundance during field study: (a) NE monsoon, (b) pre-monsoon and (c) post-monsoon seasons

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

Fig. 4 Barnacle larval movement from major spawning sites during NE monsoon season along the open coastal waters of Goa region

Fig. 5 Barnacle larval movement from major spawning sites during pre-monsoon along the open coastal waters of Goa region

Fig. 6 Barnacle larval movement from major spawning sites during post-monsoon along the open coastal waters of Goa region

Fig. 7 Barnacle larval movement from major spawning sites during NE monsoon season inside the Mandovi-Zuari estuary

Fig. 8 Barnacle larval movement from major spawning sites during pre-monsoon season inside the Mandovi-Zuari estuary

Fig. 9 Barnacle larval movement from major spawning sites during post- monsoon season inside the Mandovi-Zuari estuary

Fig. 10 Concentration of larvae reaching the sampling point inside the estuary from major spawning sites during a) NE monsoon, b) pre-monsoon and c) post-monsoon seasons.

Fig. 11 (a) wind speed and direction, (b) wind rose and (c) current speed and direction during post-monsoon season

Table 1: Distance traversed by modelled larvae from major spawning sites along the coastal waters of Goa during Dec '06, May '07 and Oct '07

Distance (in km) of larval dispersal				
Spawning location	Dec2006	May2007	Oct2007	Remarks
Arambol	38	78	22	<p>Larval transport is southward during Dec '06 and May '07, in accordance with the predominant wind direction.</p> <p>In October 2007 stations northward upto Singuirim show a northward transport but remaining stations show N-S transport with predominant transport being northward.</p>
Anjuna	32	64	35	
Singuirim	25	57	42	
Dona Paula	25	56	45 and 13	
MPT	17	53	43 and 16	
Bogmalo	26	46	50 and 16	
Palolem	14	24	10 and 6	
Galgibagh	10	16	12 and 2	

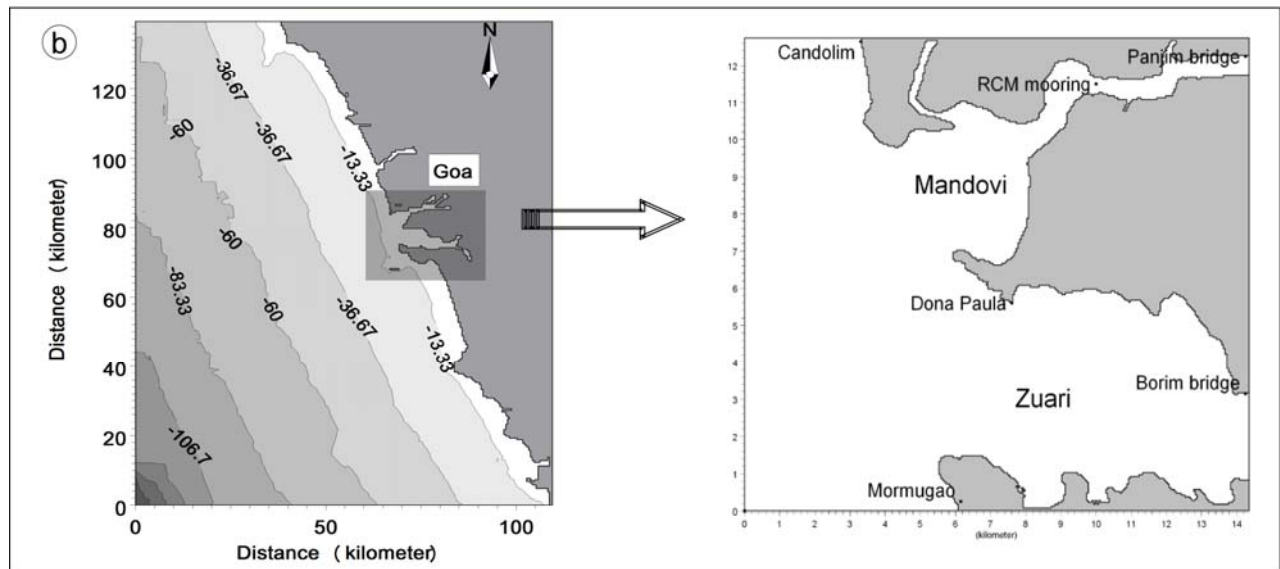
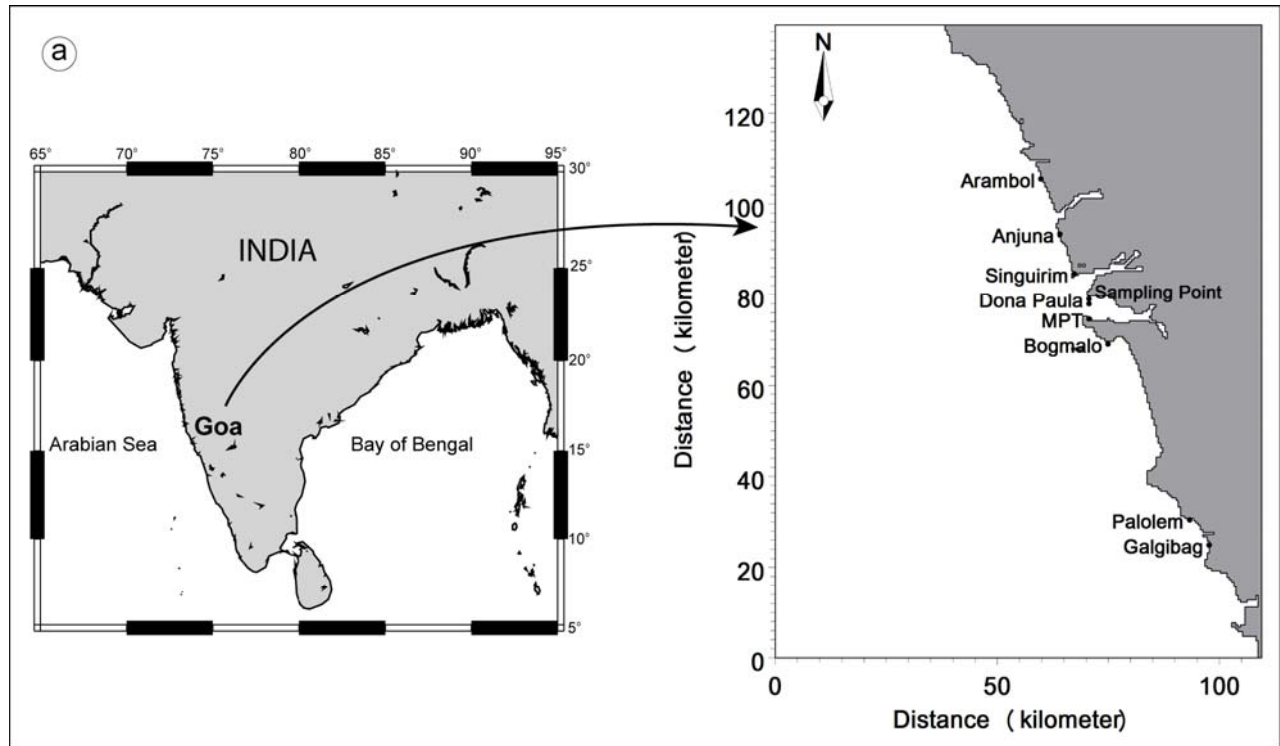


Fig.1

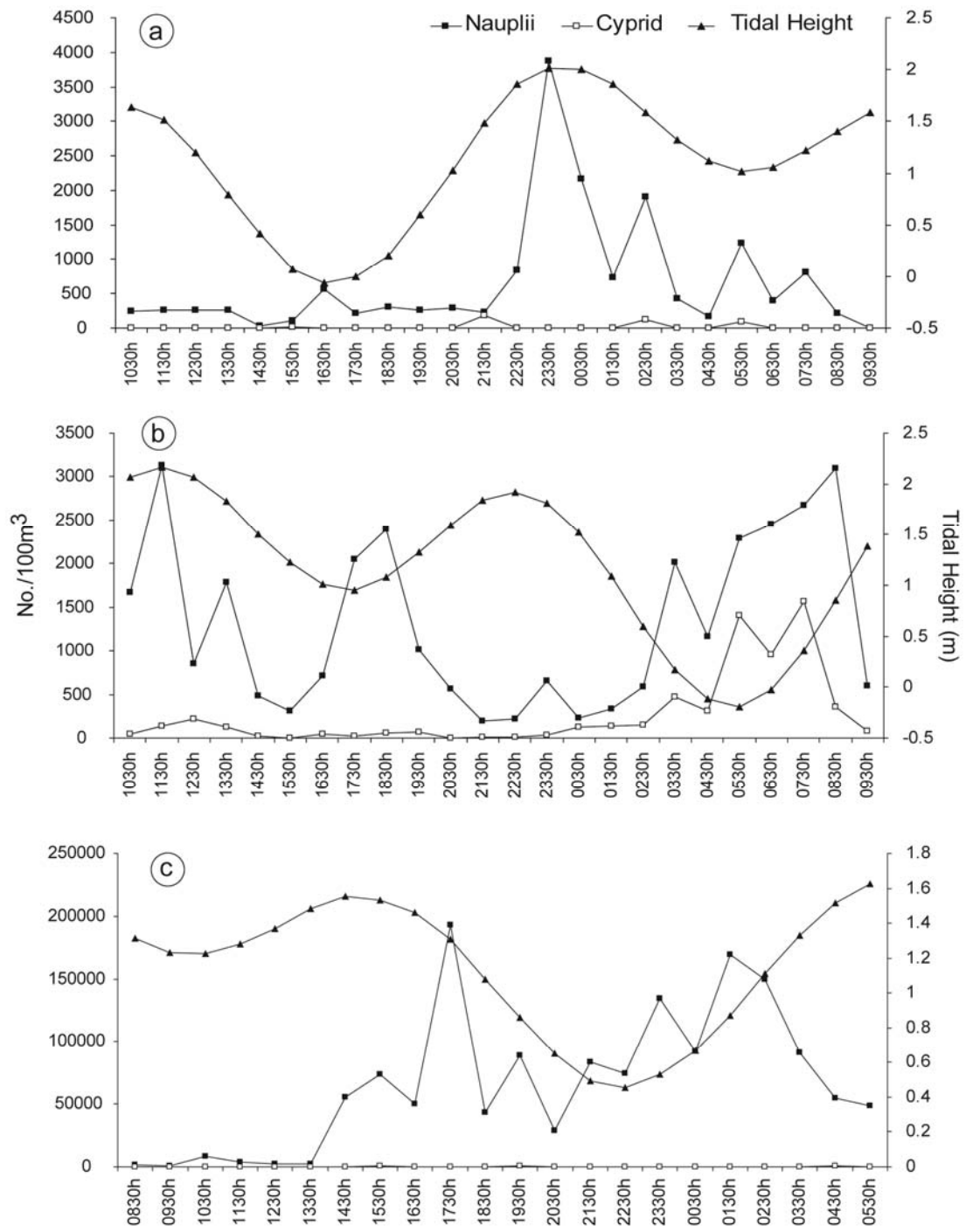


Fig.2

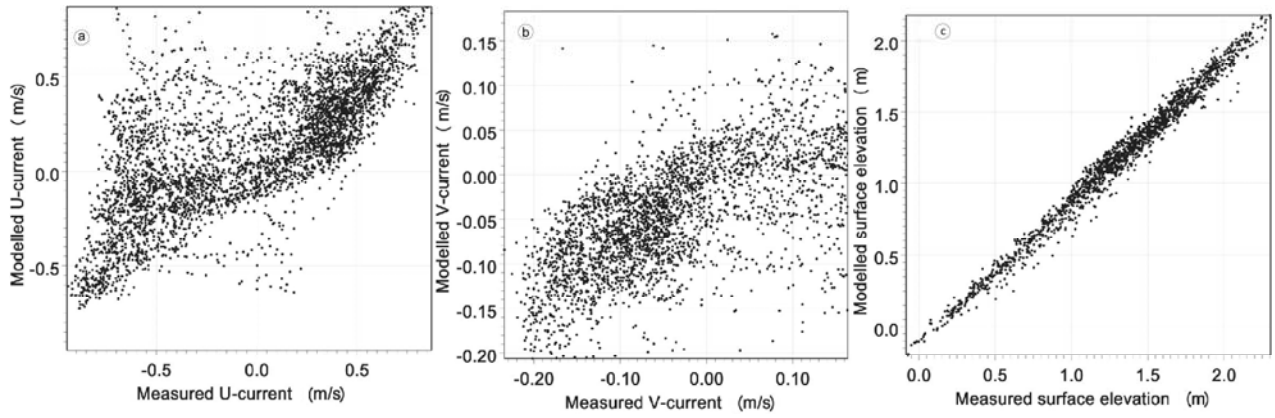


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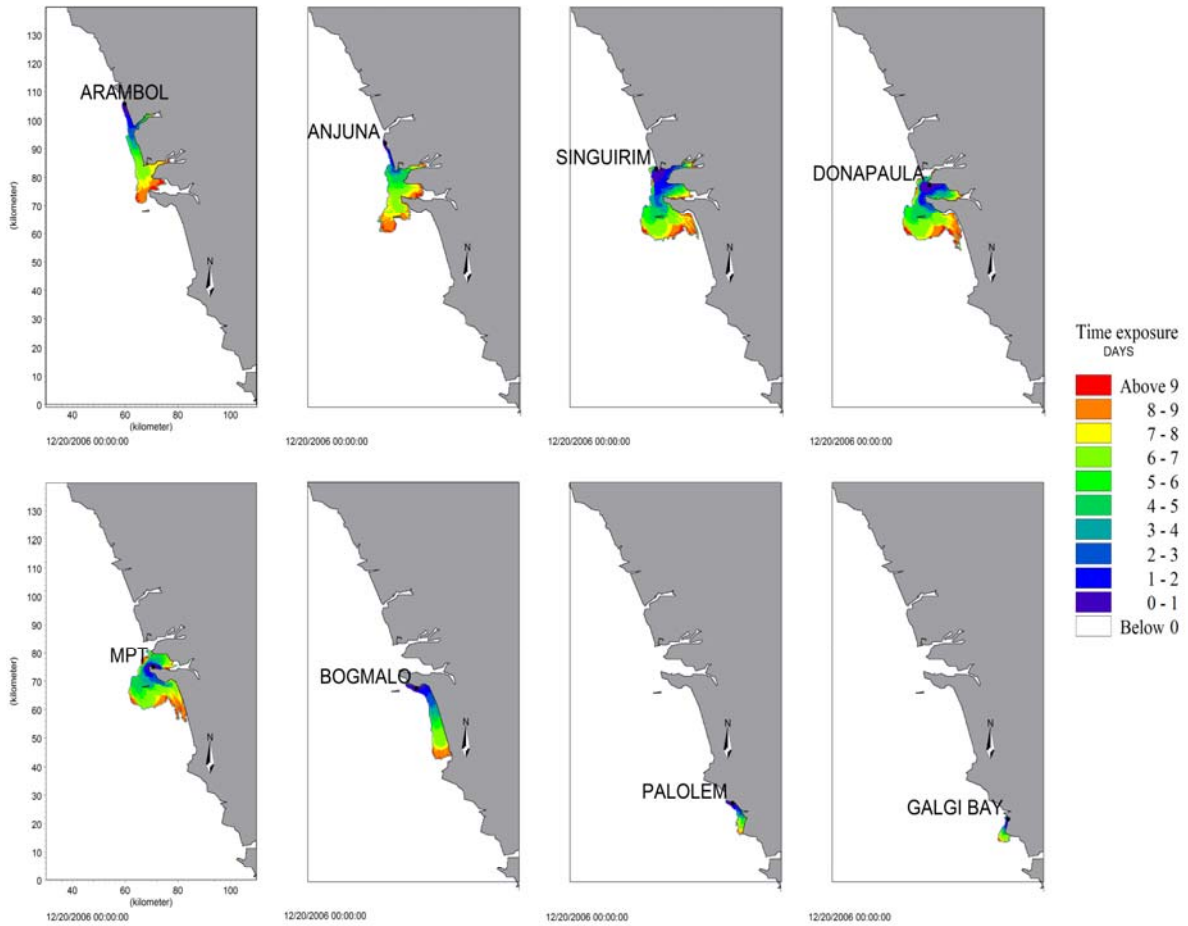


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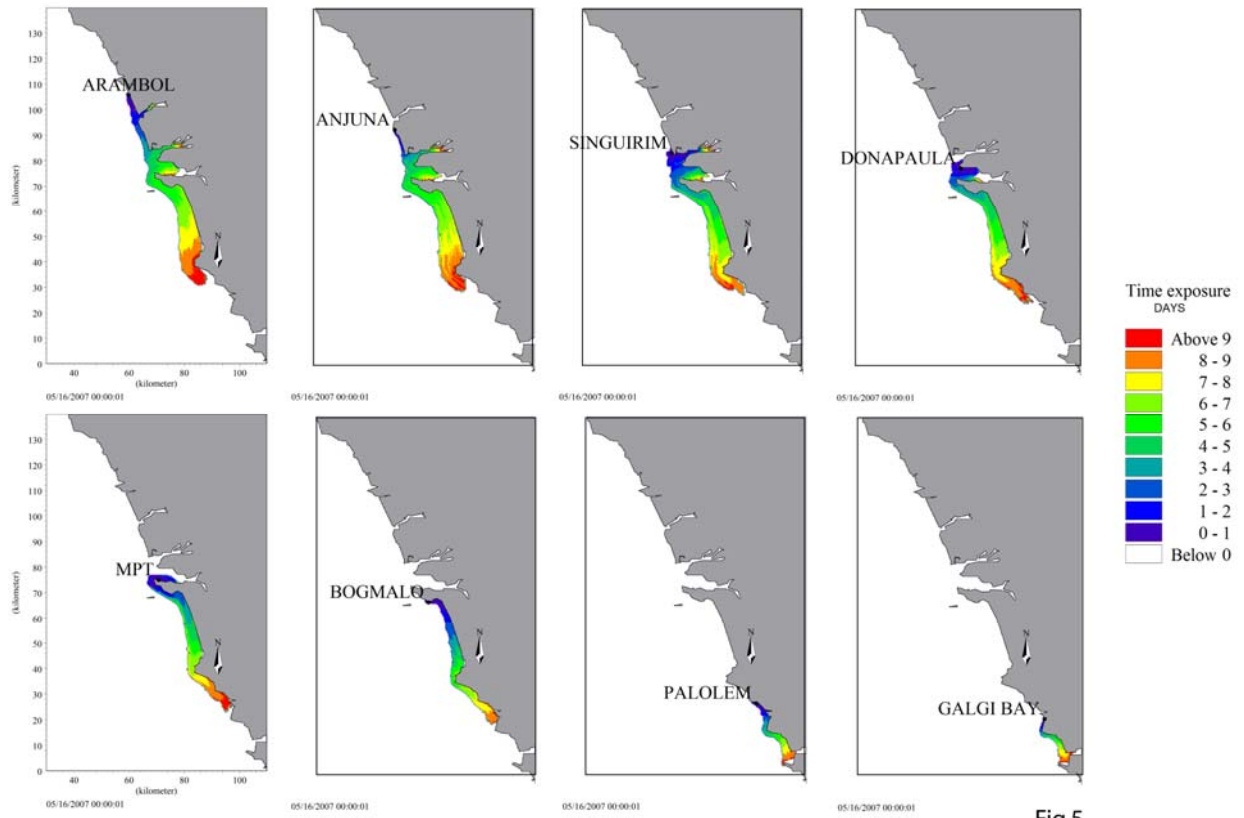


Fig.5

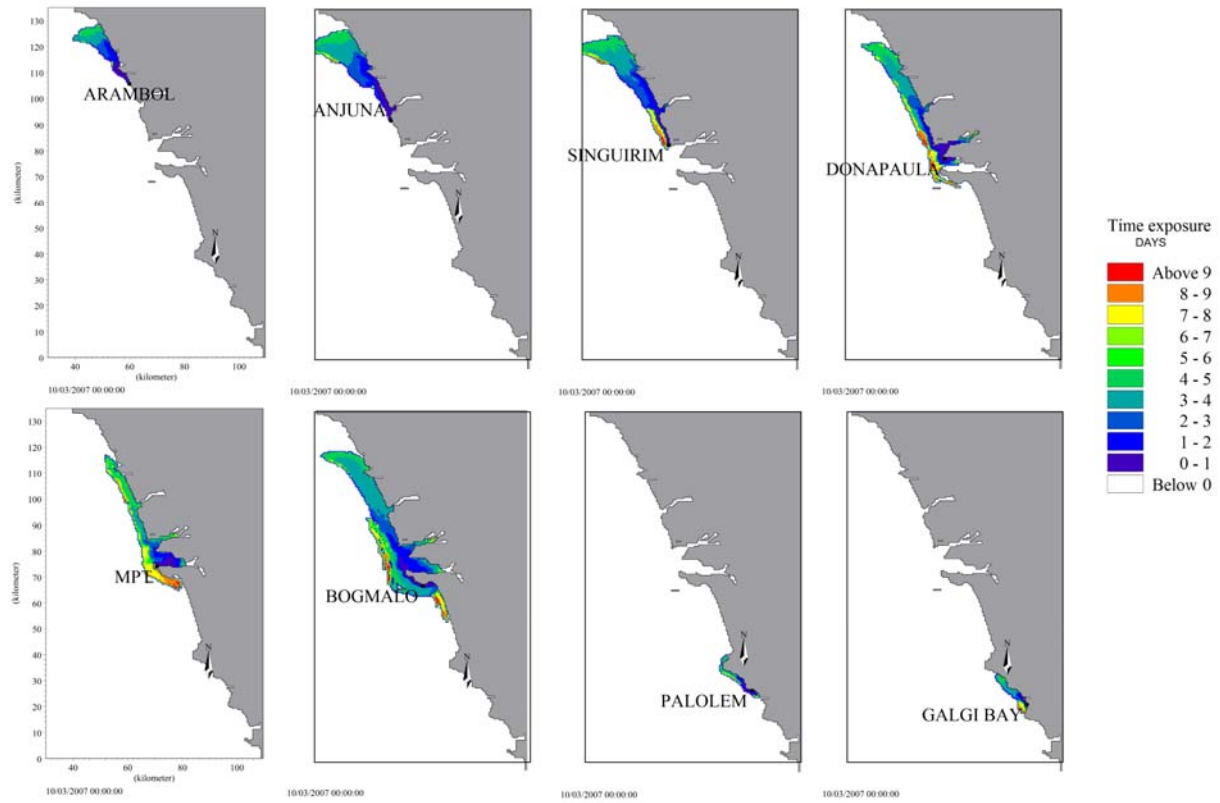


Fig.6

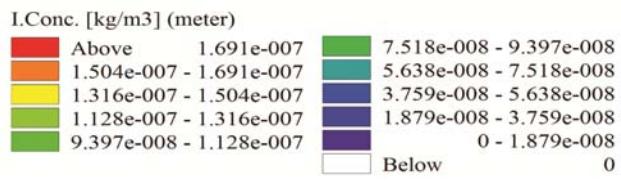
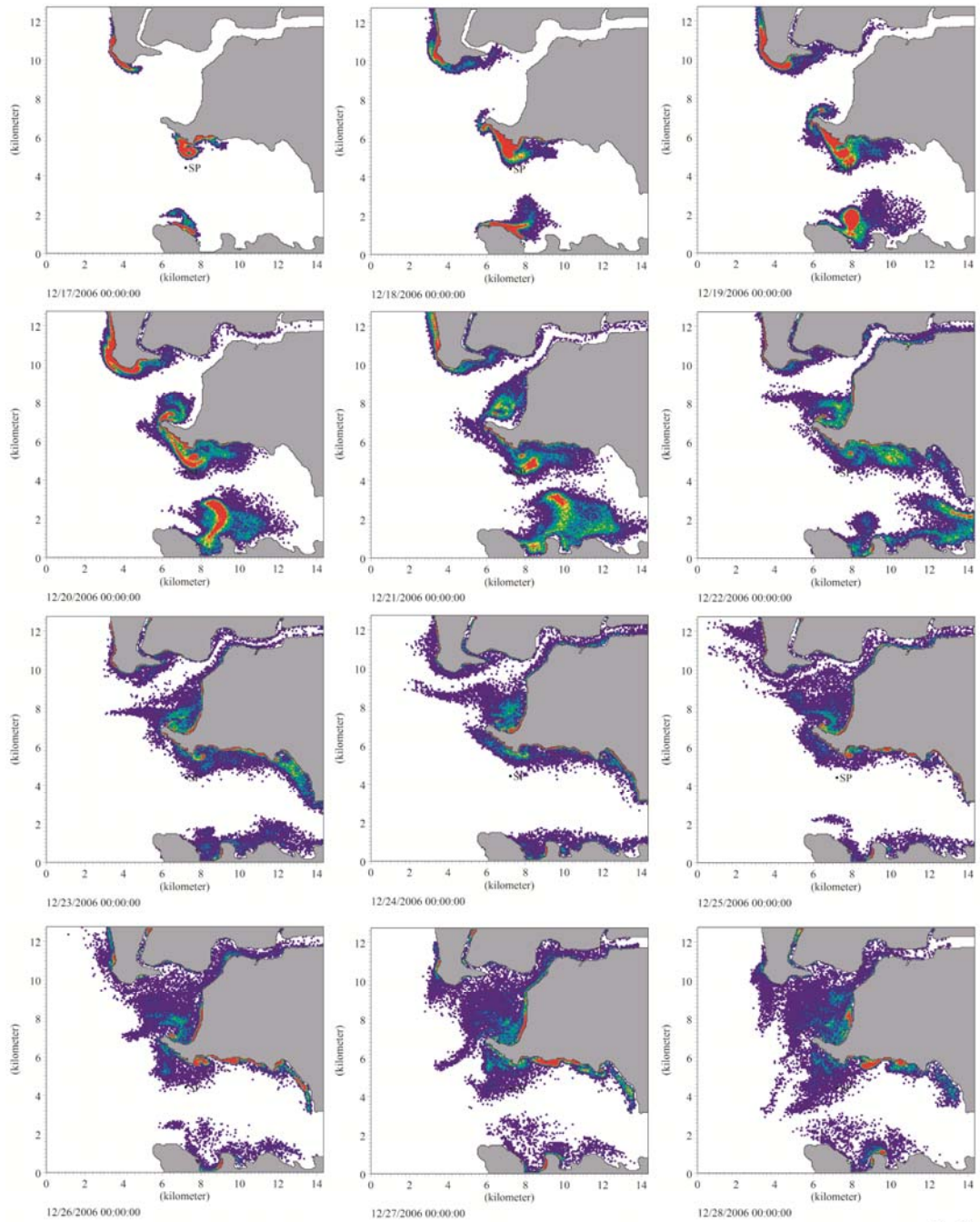


Fig.7

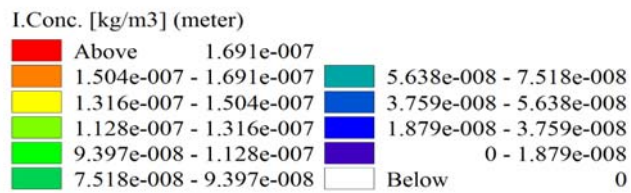
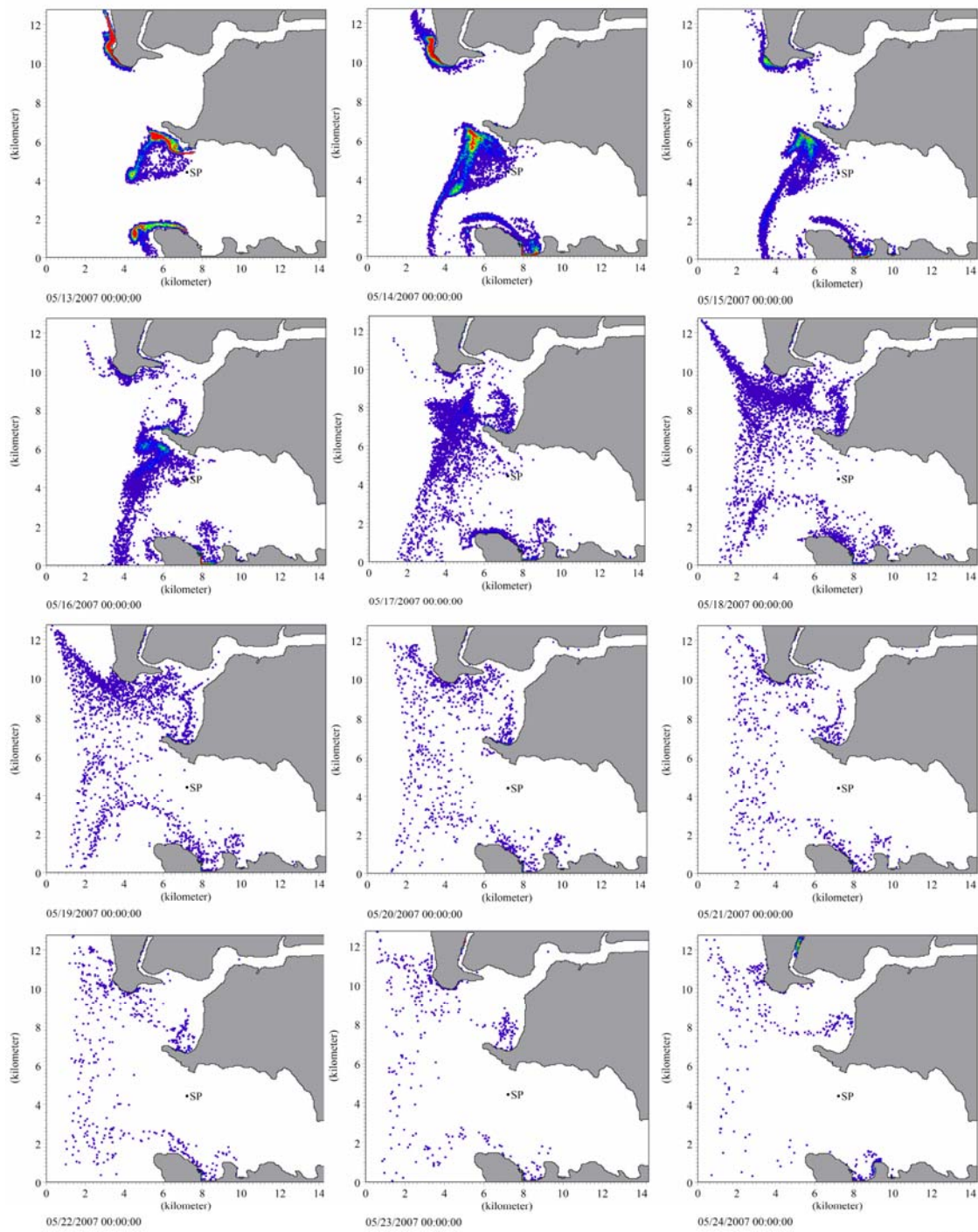


Fig.8

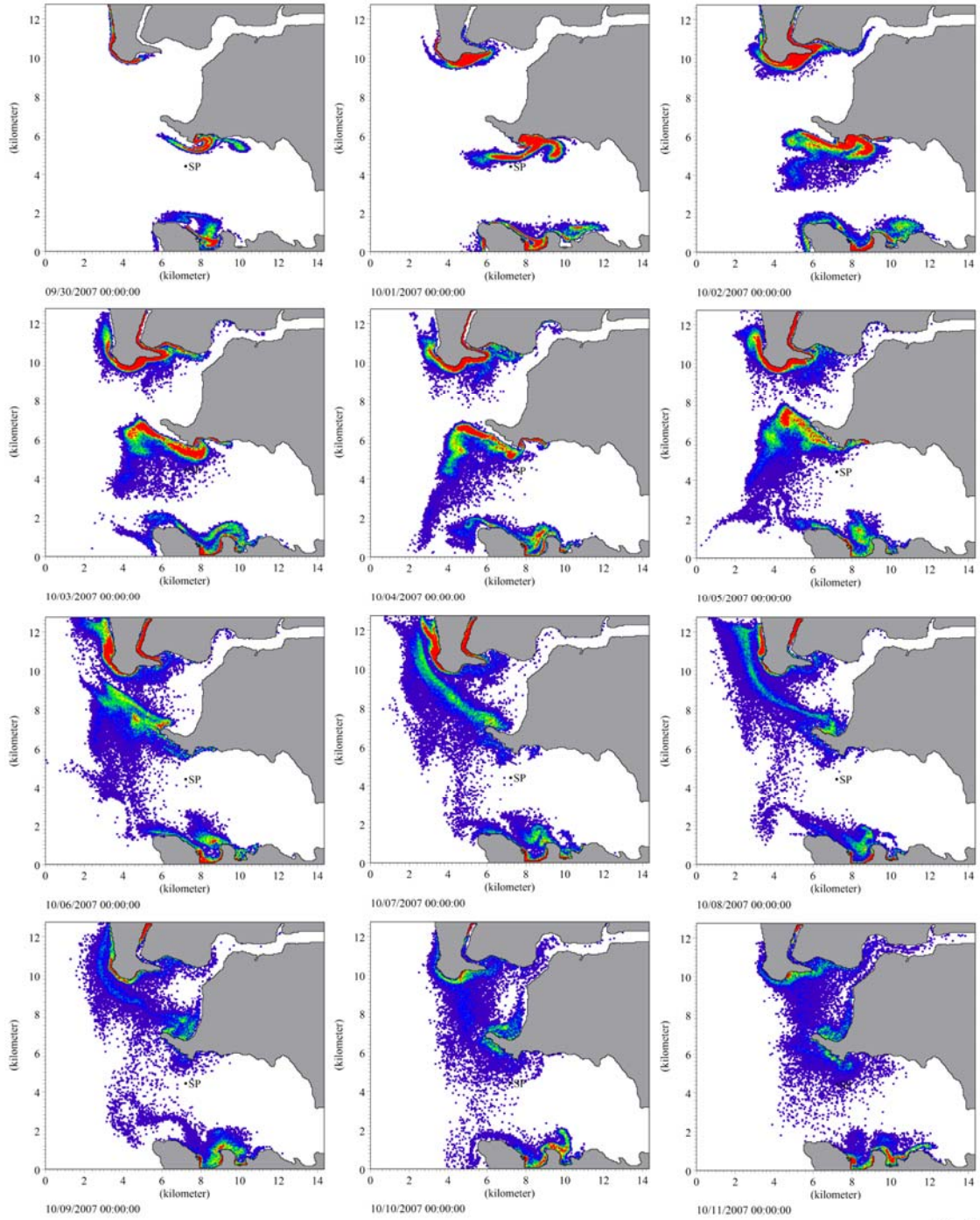
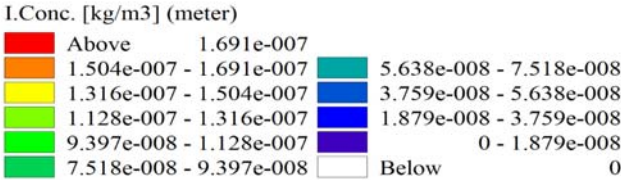
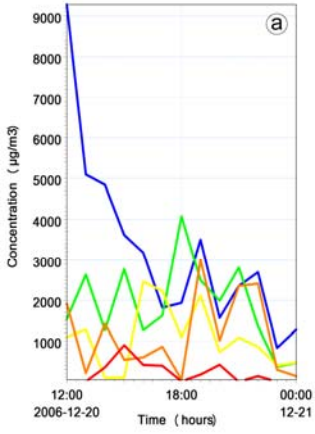
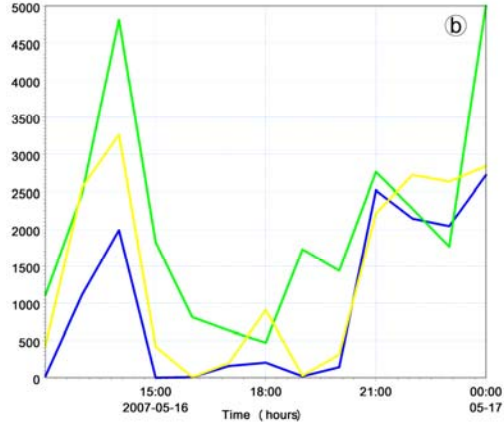


Fig.9

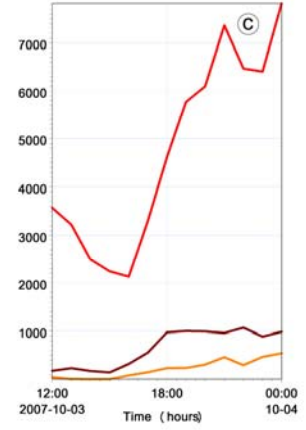




Arambol.larval.Conc. [µg/m3] [-] — blue
 Anjuna.larval.Conc. [µg/m3] [-] — green
 Singuirim.larval.Conc. [µg/m3] [-] — yellow
 Dpaula.larval.Conc. [µg/m3] [-] — orange
 MPT.larval.Conc. [µg/m3] [-] — red



Arambol.larval.Conc. [µg/m3] [-] — blue
 Anjuna.larval.Conc. [µg/m3] [-] — green
 Singuirim.larval.Conc. [kg/m3] [-] — yellow
 Bogmalo.larval.Conc. [µg/m3] [-] — red



DPaula.larval.Conc. [µg/m3] [-] — orange
 MPT.larval.Conc. [µg/m3] [-] — red
 Bogmalo.larval.Conc. [µg/m3] [-] — dark red

Fig.10

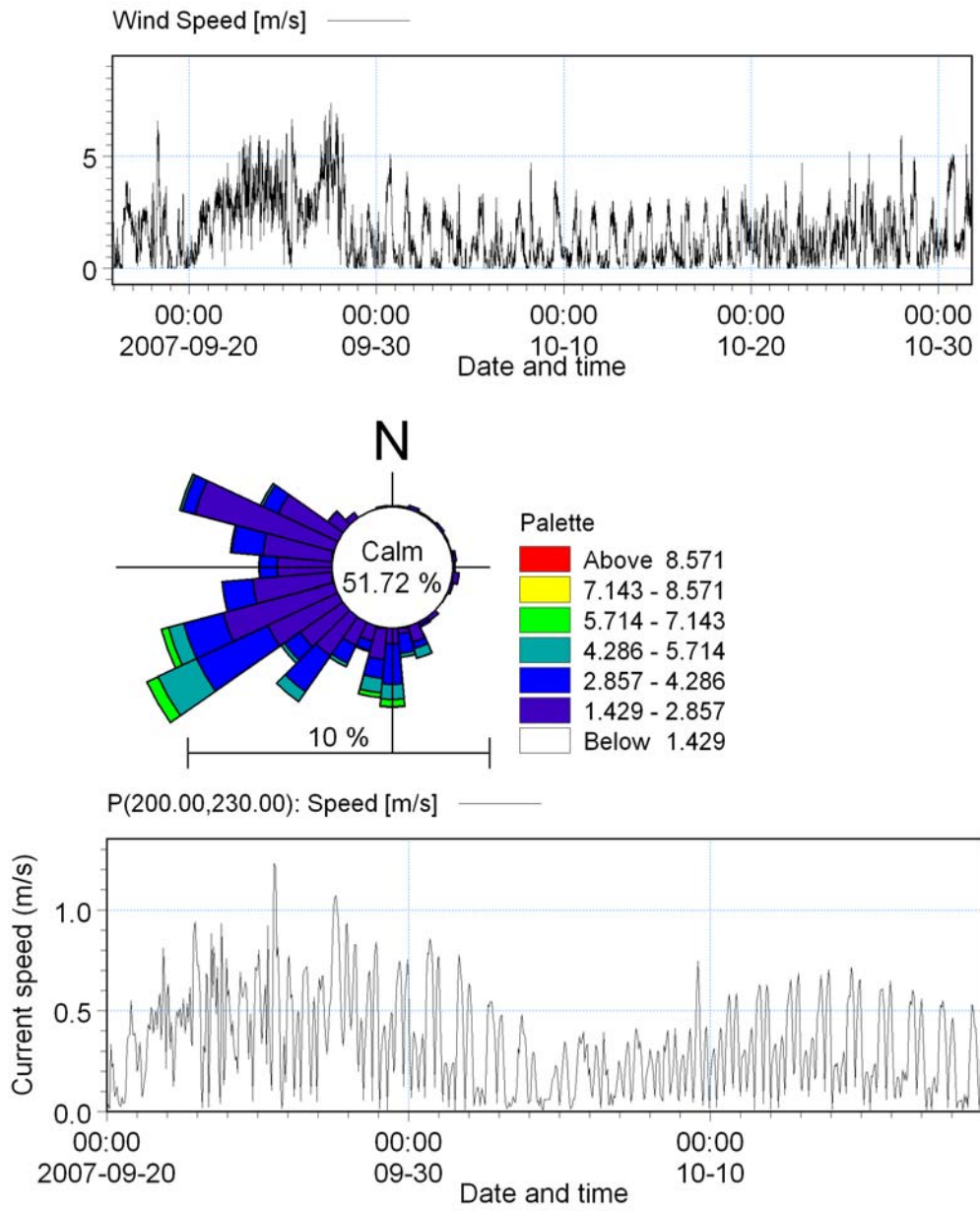


Fig. 11