Coupled bio-physical models for the transport of banana shrimps of the Sofala Bank, Mozambique

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ABSTRACT. The Sofala Bank supports an important penaeid shrimps fishery where *Penaeus indicus* and *Metapenaeus monoceros* (banana shrimp) are the two main target species. The purpose of the present paper is to investigate the roles of biophysical processes on transport of larvae of banana shrimps on the Sofala Bank. A high-resolution two-way nested Regional Ocean Modeling System (ROMS) of the Sofala Bank is developed. The ROMS solution agrees well with available observations and literature. An individual-based model (IBM) using Ichthyop coupled to the ROMS outputs is developed for the banana shrimps larvae on the bank. Simulated larval transport are influenced by the offshore mesoscale eddy activity.

KEYWORDS: IBM, mesoscale eddies, larva, *Penaeus indicus, Metapenaeus monoceros*.

1. Introduction

The Sofala Bank is located within 16° S (near Angoche) and 21° S (Bazaruto archipelago) on the western side of the Mozambique Channel between Madagascar and the African mainland. The continental shelf is generally wide and shallow, with an average depth 20-30 m. The bank is a key habitat for the shallower water penaeid shrimps in the Southwest Indian Ocean (Ivanov and Hassan, 1976). It supports an important multi-sector and multi-species shrimp fishery. The two most important species are the closely related *Penaeus indicus* and *Metapenaeus monoceros* (so-called "banana shrimps) that contribute > 80 % of the total catch (de Sousa et al., 2008). The catch has been declining from >7000 tons in 2004 – 2006 to a low level of ~ 2000 tons in 2012 (de Sousa et al., 2013). This decrease is thought to be related to a combination of detrimental environmental factors and overfishing (de Sousa et al., 2013). However, no conclusive evidence of either overfishing or environmental factors has been found on the Sofala Bank.

Shrimp catch depends to a large extent on recruitment of juveniles into the fishery. This is driven by environmental factors that influence larval transport and dispersal (Ehrhardt and Legault, 1999). It is known that banana shrimps on the Sofala Bank spawn all year round (de Sousa et al., 2008; Malauene 2015) and their eggs develop to first postlarvae within 15 days (i.e. passive pelagic larval duration – PLD). During such PLD currents can transport shrimp larvae either shoreward or offshore (Penn, 1975).

The Mozambique Channel circulation is dominated by mesoscale

eddies and rings. These eddies, and particularly dipole eddies, can generate high velocity offshore-directed boundary currents (Roberts et al., 2014). Many studies have shown that eddy-induced currents can transport coastal biotic and abiotic material offshore (Tew-Kai and Marsac, 2009; Malauene et al., 2014). It is hypothesized that shrimp larvae similarly can be transported to offshore regions where they are unable to survive. The aim of this paper is to investigate the interactive roles of biophysical processes on transport of the banana shrimp larvae in tropical, shallow waters of the Sofala Bank. In the presence of limited observational data the present study is mostly based in numerical models.

2. Model and data

2.1. Hydrodynamic ROMS model for ocean circulation

The Regional Ocean Modeling System (ROMS) is a three-dimensional, split-explicit, free-surface, topography-following vertical and horizontal sigma-coordinate ocean model (Shchepetkin and McWilliams, 2005). The ROMS_AGRIF used in this study uses a fourth-order advection scheme, which reduces dispersive property errors and enhances model resolution of smaller scale processes.

A model domain encompasses the entire Sofala Bank and the offshore adjacent waters between roughly 14 – 24° S. The model uses a structured regular square grid in the horizontal plane with 6.36 km (1\16°) resolution for the large, i.e. parent grid. For a better representation of small-scale coastal features a second fine grid was created using two-way nesting (Debreu et al., 2012); the child grid at 2.12 km (1\48°) resolution.

The model topography was derived from the General Bathymetric Chart of the Oceans (GEBCO) One Minute Grid data set (available at http://www.gebco.net/data_and_products/gridded_bathymetry_data/) and interpolated to the parent and child grid. Both parent and child grid has 50 vertical sigma-layers.

For surface forcing monthly climatologies are used. Sea surface wind stress from the Quick Scatterometer (QuikSCAT) satellite at a grid resolution of 1\2°. Surface fresh-water and heat fluxes from Comprehensive Ocean-Atmosphere Data Set (COADS) also at 1\2° resolution. Sea surface temperature (SST) from Pathfinder satellite observations at 9 km resolution.

The lateral boundaries of the model domain are open everywhere except at the coast. For the lateral open boundary conditions it was used outputs from the South-West Indian ocean Model (SWIM, Halo et al. 2014) applying the one-way nesting technique (Mason et al., 2010). Tides (ten constituents M2, S2, N2, K2, K1, O1, P1, Q1, Mf and Mm) at 1/4° resolution from the Global Inverse Tide Model data set (TPXO6.2) were also integrated into the model boundaries.

Four rivers Licungo, Zambezi, Pungue and Buzi that drain into the Sofala Bank were considered in one model experiment. Rivers were included as point sources of tracers (temperature and salinity) and momentum (realistic river flow) made available in monthly climatology by the Mozambican National Directorate of Water.

2.2. Individual-based model for larval transport

Individual-based model (IBM) is used here to simulate transport of banana shrimp larvae on the Sofala Bank. The IBM simulations were developed using Ichthyop version 3.1 (Lett et al., 2008, available at http://www.ichthyop.org) coupled to the nested ROMS model of the Sofala Bank. Ichthyop is a Lagrangian transport tool that tracks the trajectories of virtual eggs and larvae providing information of their state: position (longitude, latitude and depth), age (days) and status (alive or dead) at each time step.

Nine release areas (including spawning and non-spawning locations) were defined for the IBM simulations, based in the actual spawning locations for banana shrimp on the Sofala Bank identified by Malauene (2015). Simulations consisted of randomly releasing 30000 virtual banana shrimp eggs within the release areas every three days for five years and tracking their trajectories for 15 days (PLD). During this period simulated larvae could either stay on the bank (considered as successfully retained) or transported out (considered as lost).

2.3. Altimetry data

To evaluate the model ability to reproduce the mesoscale eddy activity, weekly "Delayed Time – DT" mapped absolute dynamic topography (MADT) at grid resolution of 1/4° from 1993 to 1999 data were used. The data combine sea surface height (SSH) observations merged from multi-satellite (TOPEX/Poseidon, Jason-1, GFO, ERS-1, ERS-2 and ENVISAT) altimeter missions processed by SSALTO/Duacs and distributed by AVISO with support from Centre National d'Etudes Spatiales (CNES, http://www.aviso.oceanobs.com), hereafter refereed to as AVISO observations.

3. Results

3.1 Simulated eddies variability, circulation and structure

The model sea surface height (SSH) and the AVISO altimetry agree reasonable well (Fig. 1A and B), in particular, the high mean SSH from the northernmost limit down the channel, the offshore low SSH centered at ~22° S and ~40° E, and the west-east SSH gradient over the slope following the bathymetry between 200 and 2000 m depth. A similar strong slope mean SSH gradient was found in another model study of the Mozambique Channel (Quartly et al., 2013).

Mean eddy kinetic energy (EKE) computed from the model SSH and from AVISO observations are in qualitative agreement (Fig. 1C and D), especially, the two centers of maximum energy one between 21-22° S and 38° E and the other between 19-20° S and 39° E. Quantitatively, the model energy doubled that of AVISO observations, suggesting that the model overestimated EKE by some ~50 %.

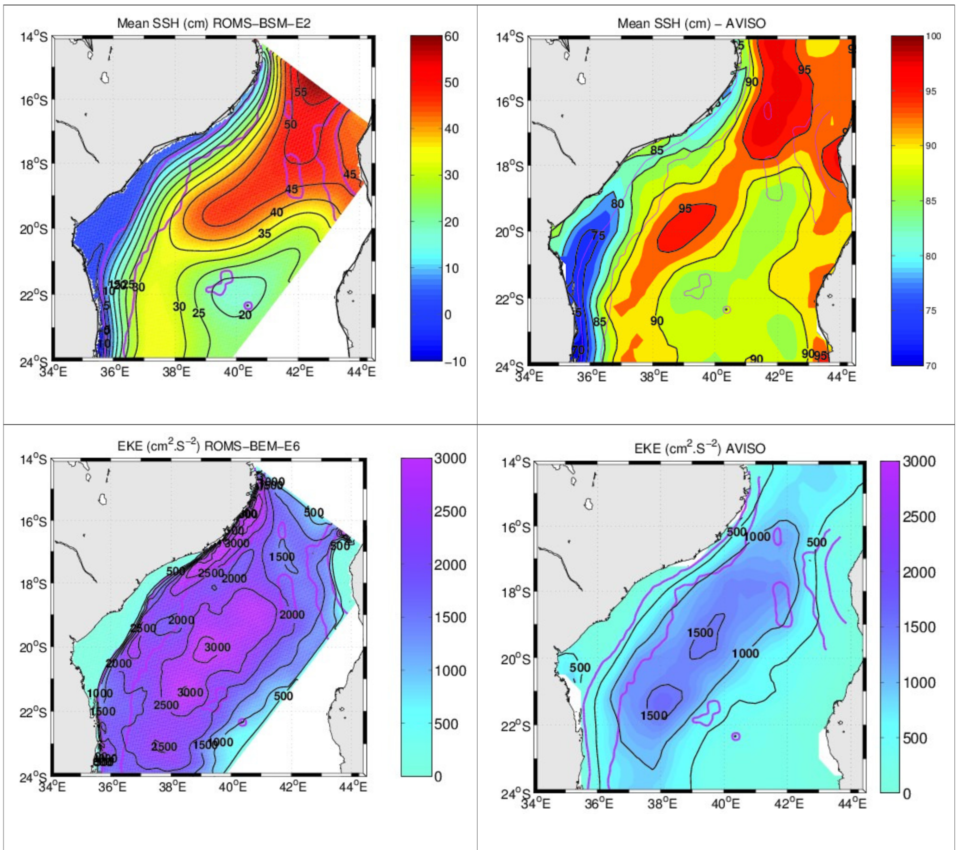

Figure 1 : Comparison between mean SSH (A) derived from ROMS years 4-10, (B) mean absolute dynamic topography derived from AVISO between 1993-1999. And mean EKE (cm^2s^{-1}) from (C) the model and (D) AVISO. Pink lines indicate the 200 and 2000 m bathymetry contours.

3.2 Simulated patterns of the banana shrimp larval transport

Simulated larvae density distribution indicated that larvae were found all over the model domain, with the high concentration on the shelf of the Sofala Bank, but some exited the bank (not shown). Snapshots of trajectories of simulated larvae show that most of the path of the larvae transported out of the bank display a circular shame (Fig. 2A, B and C), supporting the influence of the Mozambique channel eddies in advecting the banana shrimp larvae (Malauene 2015). In other cases, as depicted in Fig. 2D, nearly all larvae stayed on the bank for the full duration of the simulation. This coincided with period of weak or calm Mozambique Channel eddy activity (Malauene 2015). It is apparent that larvae originated from the southern release areas off Beira move little (Fig. 2A-D).

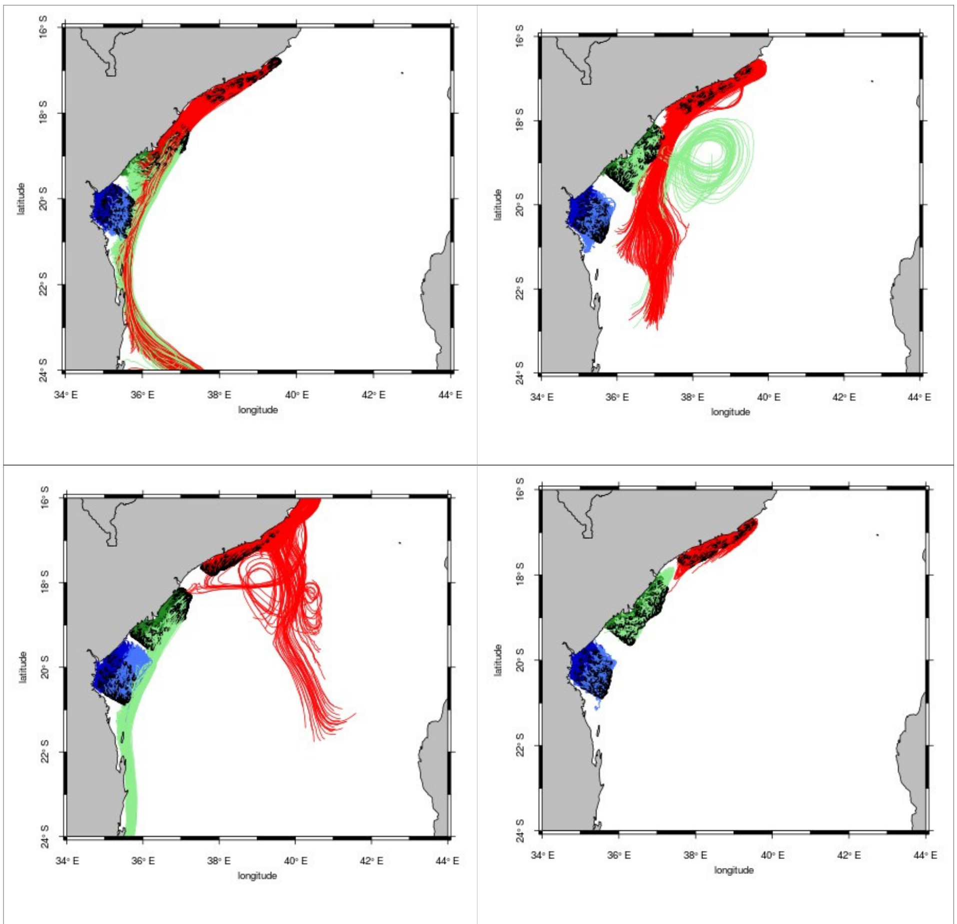

Figure 3 : Snapshots of trajectories of simulated larvae originated from the northern (red), central (green) and southern (blue) release areas. For green and blue releases areas, dark colors indicate inshore and light offshore. for simulations starting: (A) 2 February, (B) 21 March, (C) 3 June and (D) 5 July.

4. Discusion

The strong west-east gradient of mean SSH apparent over the Mozambican continental slope between the 200 and 2000 m isobaths in both the model and AVISO observations is an indication of the presence of a mean “Mozambique Current”. The model current, however, was stronger than that observed from AVISO. This probably because of the high-resolution (~6 km) of the model compared to the global, smoothing and coarser resolution (~25 km) of AVISO observations (Quartly et al., 2013).

The model overestimation of the mean EKE and thus the mean eddy variability in about 50% is gained from the SWIM climatology model used here for the lateral open boundary conditions. The elevated mean EKE from the model and AVISO, however, occurred at the same place, indicating that the model reproduce the Mozambique Channel eddy variability. According to Halo et al. (2014), the SWIM model overestimated the Mozambique Channel eddy variability relative to AVISO by about 40-50 % probably because SWIM reproduces the eddies with larger diameter and higher amplitude than AVISO.

The present study shows that the offshore highly energetic eddies of the Mozambique Channel strongly influence the Sofala Bank circulation and river plume direction. The direction and magnitude of the eddy impact depend on the eddy type, strength and proximity to the shelf. Offshore eddies have little impact on the dominant tidal region off Beira.

Offshore eddies influence the pattern of simulated larval transport on the Sofala Bank except off Beira Bay. Bay of Beira is semi-enclosed and thus protected from the impact of these eddies. Generally in the absence of mesoscale eddy activity larvae stay in the Sofala Bank. Eddies therefore are unlikely to produce a continuous declining in the catch.

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