Ocean Circulation of the Zanzibar Channel: A Modeling Approach

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1 Introduction

There are only a few studies on the ocean circulation of the Zanzibar Channel and most of them are based on only a few local measurements from which the circulation of the entire channel is inferred. Numerical models can be used to assess better the general circulation in the entire channel and get more accurate information about the circulation even in areas where no measurements are available.

The Regional Ocean Model System[1] (ROMS) is a free-surface, terrain-following ocean model that solves the three-dimensional hydrostatic primitive equations, including non-linear terms (Shchepetkin and McWilliams, 2005). It allows oceanic simulations of mesoscale and smaller areas and it is widely used by the scientific community worldwide.

Apart form the East African Coastal Current which contributes a net northward flow in the Zanzibar Channel, winds and tides are the main forces that drive the circulation in the channel. The area is affected by the monsoon winds that flow from the SE from March to October and from the NE from October to March, with short intermediate periods (Ngusaru and Mohammed, 2002). According to the study by Harvey (1977), the tidal circulation inside the Zanzibar Channel is very complex. The flood streams enter and the ebb streams exist the channel at both the north and south channel entrances. Later studies by Mohammed et al. (1993) and Shaghude et al. (2002), corroborate this circulation pattern.

For the present study, a local application of ROMS was developed to assess the circulation in the Zanzibar Channel. Numerical experiments that incorporate tides and winds were carried out.

2 Materials and Methods

2.1 Study Area

The Zanzibar Channel is a north-south orientated channel, located along the coast of Tanzania, in the western Indian Ocean (Fig. 1). Its eastern boundary is the coast of mainland Tanzania and its western boundary is the coast of Unguja Island of the Archipelago of Zanzibar. It is about 120

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[1] http://www.myroms.org

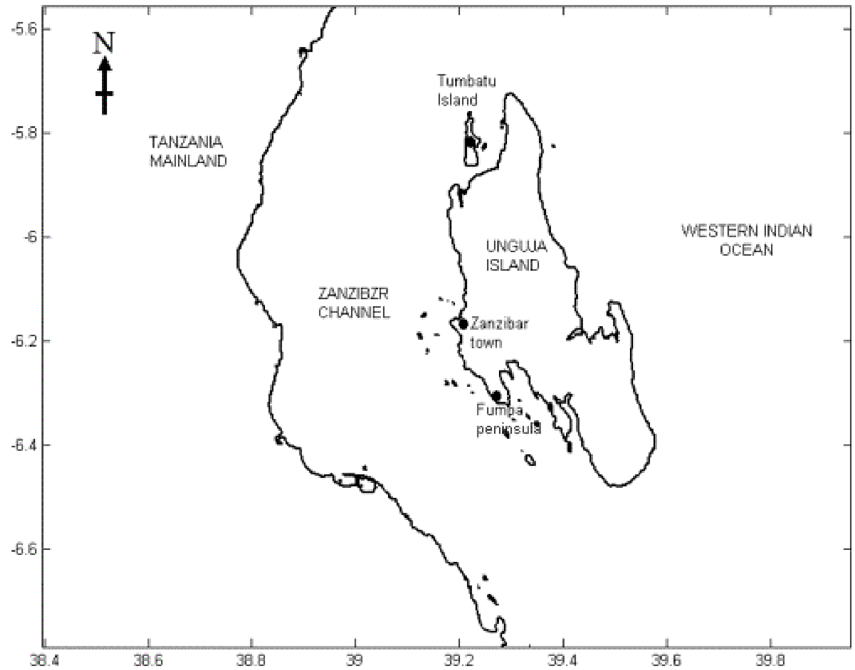

Figure 1: Location of the study area: The Zanzibar Channel

km long and 35 to 40 km wide. It is generally shallow with a depth of between 30 to 40 m in the center (Shaghude and Wannäs, 1998).

2.2 Data analysis

Coastline and bathymetric data were used to construct a curvilinear orthogonal grid, using the Matlab interface SeaGrid[2]. The resulting grid had 60 cells in the east-west direction and 100 cells in the north-south direction, covering an area of 72.4×88.4 km. The minimum depth was 2 m and the maximum 66 m with a resolution in the horizontal of approximately 1 km^2 (Fig. 2).

Monthly averages of wind data for 10 years (1996-2005) from Zanzibar airport meteorological station were analyzed. The wind conditions for the month of July (25° from true north and 7.3 m/s) was selected as the most representative of the SE monsoon. Following the same criteria the wind conditions for January (120° from true north and 8.2 m/s) were chosen as representative of the NE monsoon.

The amplitude maps of the tidal components M2, S2 and K1 for the area were extracted from the global solution of the TPXO7 model[3]. According to this, the maximum amplitudes within the channel are generated by the M2 and S2 components (1.6 and 5.5 m respectively). Its distribution along the channel is quite complex (Fig. 3), which is likely generated by the amplification of the tidal wave that is coming in through both entrances of the channel. The M2 component was selected

[2]http://woodshole.er.usgs.gov/staffpages/cdenham/public_html/seagrid/tutorial.html
[3]http://www.coas.oregonstate.edu/research/po/research/tide/global.html

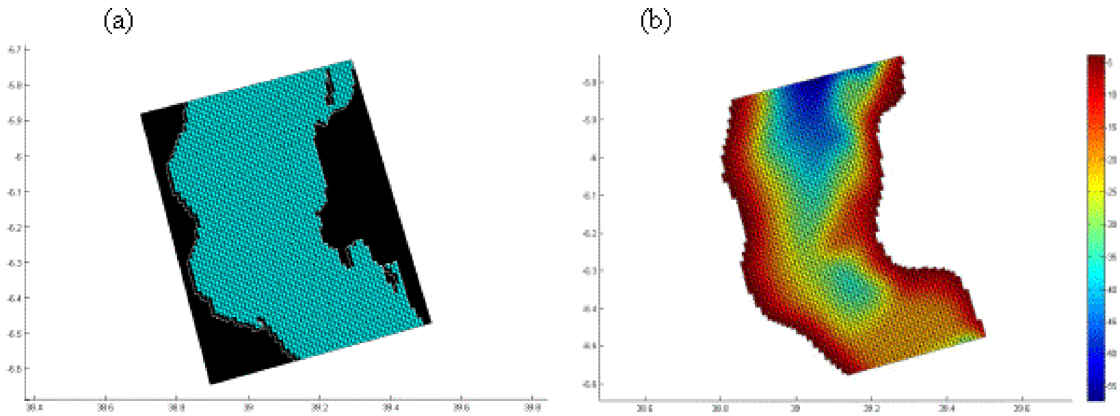

Figure 2: Land/water mask (a) and bathymetry (b) of the grid used for the numerical experiments.

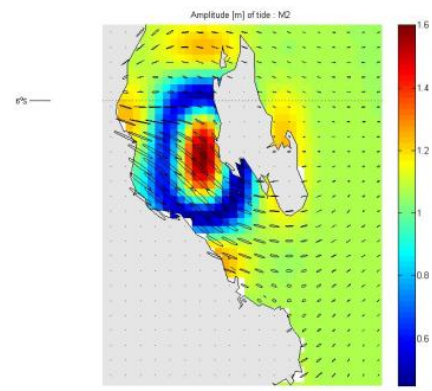

Figure 3: Distribution of amplitude (m), and tidal ellipses of the M2 tide component in the Zanzibar Channel extracted from the TPX07 model solution.

to be applied as forcing for the model because according to the TPXO7 model solution it generates higher current velocities (0.16 m/s) in the channel than the other components.

2.3 Model configuration

ROMS was configured according to the characteristics of the grid, including 16 sigma layers in the vertical. The north and south boundaries were set to be open. The time interval to solve the 3D momentum equation was set to 100 s. Constant temperature of 26°C and salinity of 34.9 o/oo were assumed.

Numerical experiments with analytical forcing, namely by NE wind, SE wind, the M2 tide component were conducted.

The wind forcing was established as a surface momentum flux uniform over the entire domain. The wind velocity vector was split into its components and the wind stress was calculated in terms of their magnitude. A linear ramp was used to increase wind magnitude from zero to its maximum during the first 2 days of modeling. After this, the wind remained constant over time. Wind

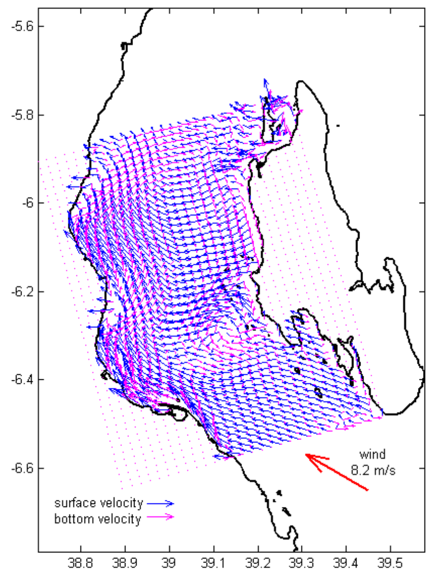

Figure 4: Field of vectors representing the surface (blue) and bottom (pink) velocities generated by 8.2 m/s SE wind.

experiments were run for 10 modeling days, after this time a stable state was achieved.

Tidal forcing was establish as a sea level perturbation at the southern and northern open boundary, with the frequency of the M2 component (12.42 hrs), and an amplitude of 0.5 m. The model itself propagates the perturbations along the domain.

3 Results and Discussion

3.1 SE wind

The SE wind generates a general surface flux towards the mainland. Surface velocity vectors follow the wind direction in the southern part of the island, up to Fumba peninsula which causes a deflection of the current. An area of minimal movement is found slightly south of Zanzibar Town. From there to the northern tip of the island the current has a predominantly westward component.

Bottom velocity vectors follow the shape of the coast on both sides of the channel and point southward along the coast of Unguja Island and northward along the mainland coast. Strong surface (27 cm/s) and bottom (16 cm/s) velocities are found around Tumbatu Island and along the coast of the mainland, where the vectors align following the shape of the coast showing a northward current (Fig. 4).

A longitudinal gradient of sea surface elevation of 5 cm towards the coast of the mainland is observed. The water is piling up towards the coast of the mainland due to the sum of the wind effort in the east-west direction and the Coriolis effect. Upwelling conditions can be expected along the coast of Zanzibar Island under this wind condition (Fig. 5).

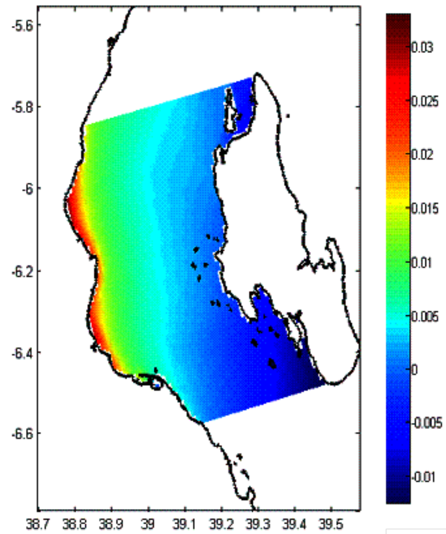

Figure 5: Distribution of sea surface elevation (m) compared with the non-perturbed level, observed when forcing the model with 8.2 m/s SE wind.

3.2 NE wind

NE wind generates southward surface currents (30 cm/s) along both coasts of the channel. Slower velocities are found in the central part of the channel and in front of Zanzibar Town where the southward surface current is deviated to the west due to the morphology of the coast and the presence of shallow reef patches and small islands. Bottom current flows southward along both coasts of the channel and northward in the center of it. Topography has a strong effect on the bottom current. It generates two gyres turning clockwise, which meet in front of Zanzibar Town (Fig. 6).

Under these wind conditions sea surface elevation shows a variation of just 1.5 cm, water accumulates towards the southern entrance of the channel and the west coast. There is no evidence of upwelling condition along the mainland coast due to the influence of the morphology of the coast, whose effect is stronger than that of the Coriolis effect (Fig. 7).

3.3 M2 tide component

For the tidal forcing there was no difference between the bottom and surface current patterns, just the speed decrease towards the bottom do to friction as it is expected, therefore vertically integrated velocities are presented as an overall result (Fig. 8).

The tidal wave with the period of 12.42 hrs (M2) coming in through both open entrances of the Zanzibar Channel generates a northward and a southward current that come into the channel during flood at both entrances, respectively, and meet in front of Zanzibar Town where a zone of minimal motion is observed (Fig. 8a). During ebb the currents diverge, flowing out from the channel (Fig. 8b). The surface velocity of the currents at the entrances of the channel during ebb and flood is approximately 10 cm/s, it decreases towards the center of the channel, being just 1 cm/s in the zone of minimal motion, in front of Zanzibar Town. This circulation pattern agrees

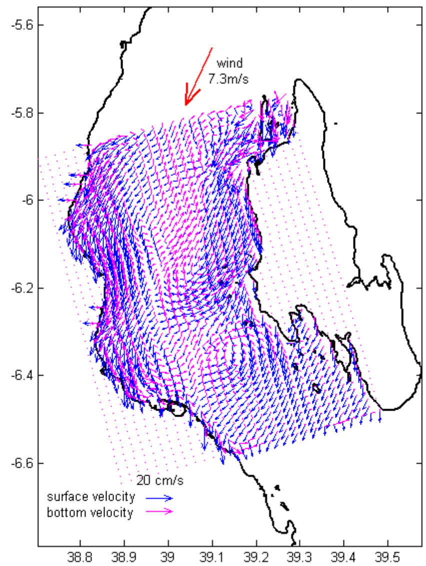

Figure 6: Field of vectors representing the surface (blue) and bottom (pink) velocities generated by 7.3m/s NE wind.

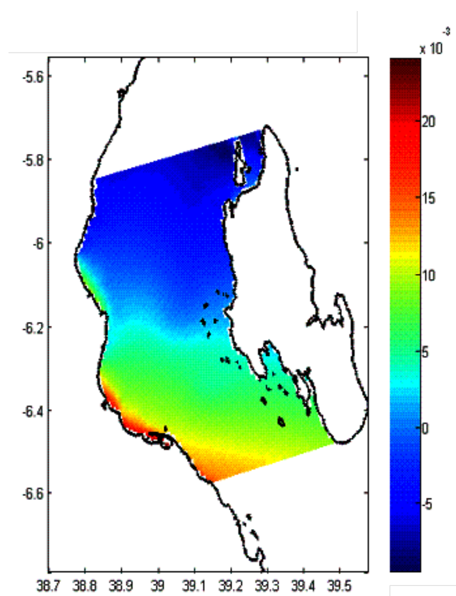

Figure 7: Distribution of sea surface elevation (m) compared with the non-perturbed level, observed when forcing the model with 7.3m/s NE wind.

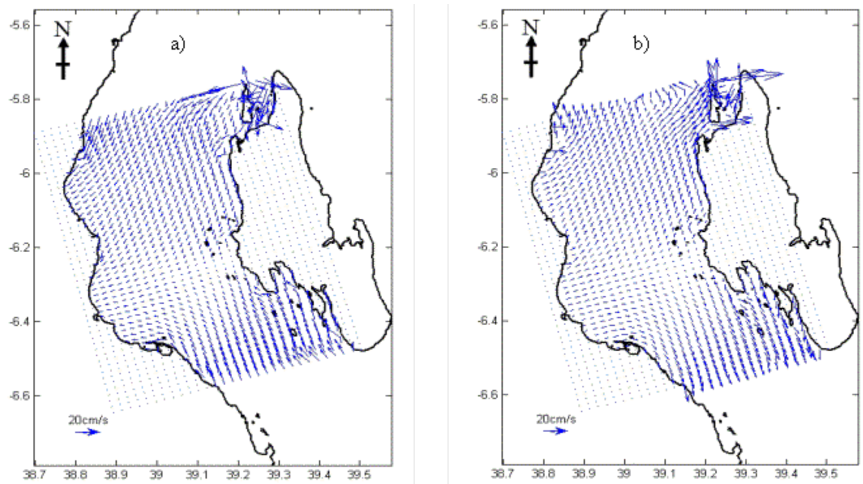

Figure 8: Circulation pattern observed during a) flood and b) ebb with the tidal wave coming in through both entrances of the channel (vertically integrated velocities).

with that described in previous studies based on direct observations (Harvey 1977; Mohammed et al. 1993; Shaghude et al. 2002).

Maximum velocities of up to 1.19 m/s at the surface were found around Tumbatu Island. This is in agreement with the observations by Harvey (1977), who observed the maximum velocities where the streams flow past the north-east corner of Zanzibar Island.

The gradient of the sea surface elevation along the channel is minimal. The maximum and minimum ($\pm$ 0.5 m) is found in the area of no motion, but the model does not magnify the amplitude of the prescribed tidal wave to reproduce the amplitude map of the TPXO7 solution (Fig. 3).

4 Conclusion

Qualitatively the results of the model reproduce the main circulation patterns previously reported for the Zanzibar Channel (Harvey 1977; Mohammed et al. 1993; Shaghude et al. 2002). The range of velocities generated by the model is also within the range of velocities previously reported, however, more direct measurement are needed to validate the results.

As the present study is a first semi-idealized modeling approach the presented result should be considered with caution.

Further development of the model application presented, including real forcing fields and local oceanographic data, is encouraged in order to get more realistic results.

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References

Harvey, J.: 1977, Some aspects of the hydrography of the water off the coast of Tanzania: A contribution to CINCWIO. *University Science Journal - University of Dar es Salaam*, **3**, 53–92.

Mohammed, S., A. Ngusaru, and O. Mwaipopo: 1993, Determination of the effects of pollution on coral reefs around Zanzibar Town. A technical report to the National Environment Managment Council), Dar es Salaam, Tanzania. Technical report, Institute of Marine Sciences, Zanzibar, University of Dar es Salaam.

Ngusaru, A. and S. Mohammed: 2002, Water, salt and stoichiometrically linked nutrient budgets for Chwaka Bay, Tanzania. *Western Indian Ocean J. Mar. Sci.*, **1**, 97–106.

Shaghude, Y. and K. Wannäs: 1998, Morphology and sediment distribution of the Zanzibar Channel. *Ambio*, **27**, 729–733.

Shaghude, Y., K. Wannäs, and S. Mahongo: 2002, Biogenic assemblage and hydrodynamic settings of the tidally dominated reef platform sediments of the Zanzibar Channel. *Western Indian Ocean J. Mar. Sci.*, **1**, 107–116.

Shchepetkin, A. and J. McWilliams: 2005, The Regional Ocean Modeling System: A split-explicit, free-surface, topography following coordinates ocean model. *Ocean Modelling*, **9**, 347–404.