academicJournals

Vol. 5 (1), pp. 1-7, January, 2014
DOI: 10.5897/JOMS2013.0100
ISSN 2141-2294 ©2014 Academic Journals
http://www.academicjournals.org/JOMS

Journal of Oceanography and Marine Science

Full Length Research Paper

Modelling the dynamics of the Tanzanian coastal waters

Shigalla B. Mahongo[1]* and Yohanna W. Shaghude[2]

[1]Tanzania Fisheries Research Institute, Institute HQ, P. O. Box 9750, Dar es Salaam, Tanzania.
[2]Institute of Marine Sciences, University of Dar es Salaam, P. O. Box 668, Zanzibar, Tanzania.

Accepted 28 November, 2013

A numerical modeling study was carried out using the Regional Ocean Modeling System (ROMS) for the Tanzanian coast to investigate the seasonal dynamics of water circulation, temperature and salinity. The model results indicated the presence of an eddy on the surface that develops during the Northeast (NE) monsoon and which has not been documented previously. The study also revealed that, the core of the East African Coastal Current (EACC) passes adjacent to the coast, just off the three major islands of Pemba, Zanzibar, and Mafia. There are localized patches of strong currents parallel and adjacent to the mainland coast, with magnitudes that are influenced by the coastline configuration, bottom topography and the extent of exposure to the main stream of the EACC. The current speeds along the coast of Tanzania are lowest in February and March, and highest in July, August, and November but generally not exceeding 1 ms^{-1}. Surface salinities generally vary between 34.8 and 35.5, whereas surface temperatures range from a minimum of 25.0°C to a maximum of 30.2°C. The modelled salinity and temperature profiles are similar to those observed from field observations of previous investigations.

Key words: Regional Ocean Modeling System (ROMS) model; seasonal variations; water circulation; salinity; water temperature; Tanzanian coast.

INTRODUCTION

The most important climatic phenomenon affecting seasonality in east Africa is the Inter-Tropical Convergence Zone (ITCZ), which shifts its position annually to create the northeast (NE) and southeast (SE) monsoons (McClanahan, 1988). Along the coast of Tanzania, the NE monsoons occurs from November to March, and the SE monsoons from April to October (Newell, 1957; Mahongo et al., 2012). The NE monsoon winds are lighter and predominantly northerly (blowing from north to south), while the latter are usually strong and predominantly southerly (blowing from south to north). March and October are the transition periods when winds tend to subside. During this period of transition, there is reversal from the NE to the SE Monsoon and vice versa, respectively (Iversen et al., 1984; Mahongo et al., 2012).

Despite the presence of the two nearly opposing monsoon wind systems, the dominant current prevailing along the Tanzanian coast (Figure 1) is due to the East African Coastal Current (EACC), which flows Northwards throughout the year (Newell, 1959). The EACC originates from the South Equatorial Current (SEC) which flows from east to west all year round at around 12°S. Further, the EACC is the main surface layer of water bathing the continental shelves of Kenya and Tanzania with nutrient-poor mid-ocean water resulting into low biological

*Corresponding author. E-mail: shigalla@tafiri.go.tz. Tel: +255 22 2650045. Fax: +255 22 2650043.

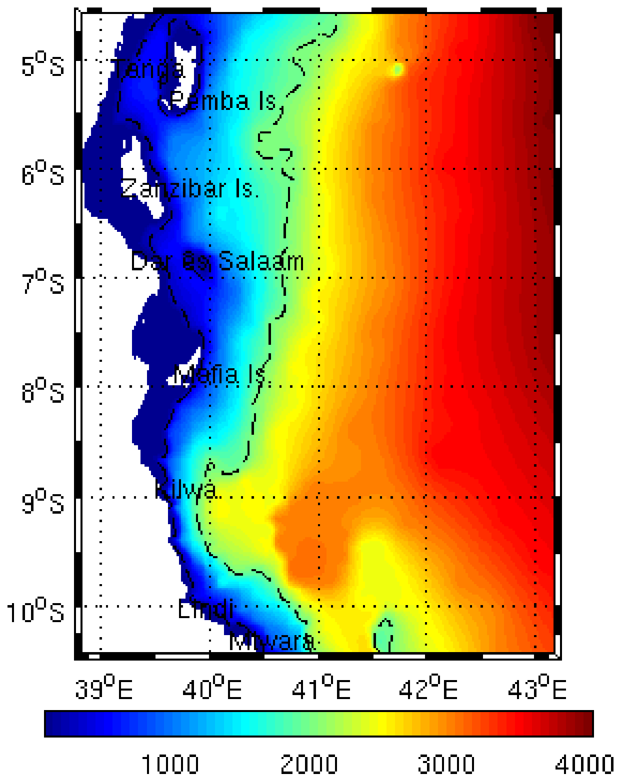

Figure 1. Plot showing the bathymetry of the study area. The legend indicates depth from the surface in meters.

productivity along the coast (FAO/UNEP, 1982).

Thus, one of the most important features that distinguish the EACC from the other ocean current systems is its monsoon dependence. During the SE monsoon season, the EACC is accelerated by the south easterly trade winds and consequently, the current speed is relatively high (1.5 to 2 ms^{-1}). During the NE monsoon season, the current is retarded by the north easterly trade winds along this coast and as a consequence the current speed is relatively low (about 0.5 ms^{-1}), and it is reversed from the Equator northwards. The reversed current meets the EACC at about 1°S, where both are deflected out to the sea forming the ECC. The largest manifestation of the seasonal cycle is therefore the reversal of the monsoon winds and the associated changes in local climate.

In previous studies Newell (1957) observed that, the surface temperature maximum (29.1°C) occur in March and April (at the end of the NE monsoon and start of the SE monsoon, respectively) and the surface temperature minimum (24.8°C) occur in September (towards the end of the NE monsoon). Other outstanding studies on the physical processes of the Tanzanian coastal waters include those of Newell (1957), McClanahan (1988), Swallow et al. (1991) and Nyandwi and Dubi (2001). Whereas McClanahan (1988) focuses on seasonality of the coastal waters, the major coastal currents are discussed by Newell (1957) and Swallow et al. (1991), while Nyandwi and Dubi (2001) discuss on the influence of the monsoon wind systems in the beach sediment dynamics.

There are four water masses that have been documented in the Tanzanian offshore waters, characterized by salinity (and oxygen) and occurring at increasing depths (Newell, 1957, 1959). They are: Tropical surface water (above 100 m) flow to the west characterized by high salinity (and high oxygen), Arabian sea water convergence at ~ 1000 m characterized by high salinity (and low oxygen), Antarctic intermediate water flow to the north characterized by low salinity (and high oxygen), and north Indian deep water flow to the south characterized by high salinity (and low oxygen). According to Warren et al. (1966), the tropical surface water originates from the SEC, which is in turn derived from the Bay of Bengal and the eastern Indian Ocean.

However, due to lack of long term systematic observations in the coastal and offshore waters of Tanzania, information about various oceanographic features remains fragmented. The present study has therefore used the Regional Ocean Modeling System (ROMS) to model the seasonal dynamics of the Tanzanian coastal waters for the purpose of upraising the fragmented information from past studies. ROMS is a free-surface, topography-following primitive equations ocean model (Shchepetkin and McWilliams, 2005). It is a complex, new state-of-the-art model with many options and capabilities.

The model can be configured for any region of the world ocean ranging from local to basin scale. It may include for instance, several coupled models for biogeochemical, bio-optical, and sediment applications that are widely used by the scientific community in a diverse range of applications (Wilkin et al., 2005).

Existing models of the Indian Ocean do not quite resolve the Tanzanian coast. For instance, the most recent work by Hermes and Reason (2008), which used ROMS to model the South Indian Ocean thermocline ridge/dome and its annual cycle, was limited to an area between 10°N to 20°S and 40°E to 110°E. The domain excluded a large portion of the present study, which includes the narrow continental shelf that harbor productive and critical coral reef systems and fisheries habitats, the Tanzanian Territorial Sea as well as the Exclusive Economic Zone (EEZ) (Figure 1).

Nevertheless, recent ROMS modelling experiments have been focused on the Zanzibar Channel (Mayorga-Adame, 2007; Garcia-Reyes et al., 2009). The major focus of these recent study campaigns were to undertake numerical modelling of the seasonal cycle, carry out experiments that incorporate tides and winds, and collect field measurements for model validation. The main objective of the present study was to configure ROMS for the coastal and offshore waters of Tanzania. Specifically, the study intended to generate appropriate boundary and forcing input files describing the seasonal cycle to force the ROMS application to configure ROMS for our application and model validation using *in-situ*

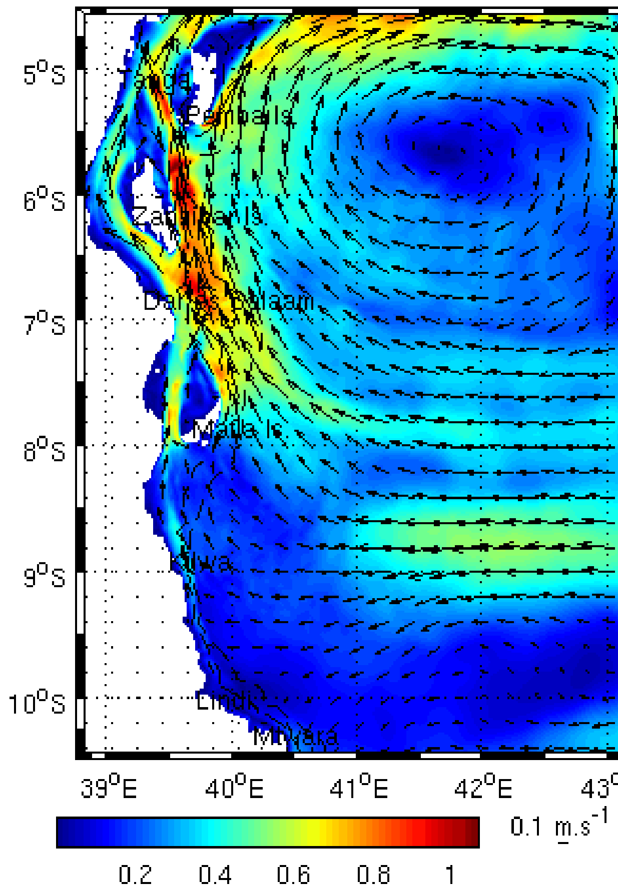

Figure 2. Surface current vectors in August representing typical conditions during the NE monsoon. The eddy is clearly discernible at around 5.5°S. The legend represents the current speed in ms^{-1}.

observations and monthly climatology of the parameters from global databases.

DATA AND METHODS

The model domain of the present study extends from the northern Tanzanian boarder with Kenya to the southern Tanzanian boarder with Mozambique, and therefore relatively larger than the domains of other similar modeling studies (Mayorga-Adame, 2007; Garcia-Reyes et al., 2009). It spans between 4.5°S to 10.5°S and 37.25°E to 43.25°E, including the three major islands of Zanzibar, Pemba, and Mafia, and incorporates the furthest point of the EEZ (Figure 1).

The domain consists of a rectangular coastal section with an easterly extent of about 500 km and a northerly extent of about 650 km. The coastal section enclosed in the model domain is of significant socio-economic importance, which includes: navigation, artisanal fishing, deep water fishing, natural gas, petroleum exploitation, etc. The results of the model will therefore be useful to the policy and decision makers, particularly those dealing with the fishery resource management and the petroleum industry.

In this study, the model was configured using ROMS tools version 2.1 (Penven et al., 2010). The grid defining the bathymetry of the Tanzanian coast and offshore waters, suitable for oceanographic modeling, was derived from the General Bathymetric Chart of the Oceans (GEBCO) at 1° resolution (Figure 1). The resulting grid was discretized by a uniform orthogonal Cartesian grid with 269 cells in the east-west direction and 363 cells in the north-south direction - with a resolution of 1.84 km. In the vertical, 20 sigma levels were used. The western boundary of the model domain was set to be closed while the remaining boundaries of the model domain (northern, eastern, and southern) were set to be open.

Initial and boundary conditions were obtained from the World Ocean Atlas (WOA-2005) global database (Conkright et al., 2002), while surface forcing was generated from actual long-term atmospheric observations of the 2005 Comprehensive Ocean-Atmosphere Data Set (COADS-2005) at 1/2° resolution (Da Silva et al., 1994). Sea Surface Temperature (SST) data (with resolution of 9.28 km) was archived from Pathfinder satellite observations (Casey and Cornillon, 1999). The control run was forced with monthly mean wind stresses computed from Quick Scatterometer (QuikSCAT) (Liu et al., 1998).

The model was configured with a 240 s time step size, in accordance with the Courant-Friedrichs-Lewy (CFL) stability criterion. The data were saved on a daily basis and from this model output, climatological monthly means were created. The model was then allowed to run for 10 complete years to achieve stabilization. The results presented are for the tenth year of the seasonal model output. To validate the model results, the SST output for the month of April were compared with monthly climatologies from satellite derived MODIS and argo floats datasets.

The MODIS data spanning 11 years (2003 to 2013) were first downloaded from ERDDAP at URL: *http://coastwatch.pfeg.noaa.gov/erddap/index.html*, and then averaged using BILKO software to produce the monthly climatology. Similarly, the argo floats data spanning 7 years (2007 to 2013) were first downloaded from the national oceanic and atmospheric administration (NOAA) National Oceanographic Data Centre at URL: *http://www.nodc.noaa.gov/argo/floats_data.htm*, and then analyzed using ODV software. The results of the model were further compared with observations from previous studies on currents, salinity, and temperature. This synergy between previous observations and ROMS is important for affirming the results of our model and also for providing insights on how future studies could be designed.

RESULTS AND DISCUSSION

The surface currents during January in the NE monsoon are shown in Figure 2. The model results indicate that, the major stream of the EACC passes closer to the coast, just off the three major islands of Mafia, Zanzibar, and Pemba. Few localized patches of strong currents are also discernible parallel and adjacent to the coast, with strengths that are possibly influenced by the coastline configuration, sea bottom topography, and the extent of exposure to the main stream of the EACC. The current speeds are generally less than 1 ms^{-1}, being lowest in March (0.05 to 0.55 ms^{-1}) and February (0.1 to 0.6 ms^{-1}), and highest in August and November (0.1 to 0.9 ms^{-1}).

In the offshore, the surface currents originate from the SEC and generally flow from the southeast and easterly directions. On approaching the Tanzanian coast, the currents turn northwards to form the EACC at about 9°S

Table 1. Modelled monthly mean surface temperatures and salinity along the coast of Tanzania.

Month	Temperature (°C)	Salinity
January	27.2 - 29.2	35.2 - 35.5
February	27.0 - 29.0	35.1 - 35.4
March	28.0 - 29.8	35.0 - 35.4
April	29.0 - 30.2	34.8 - 35.3
May	28.6 - 29.6	34.8 - 35.1
June	27.4 - 28.6	34.5 - 35.1
July	25.2 - 26.6	35.0 - 35.2
August	25.2 - 26.6	35.0 - 35.2
September	25.0 - 26.6	35.1 - 35.3
October	25.64 - 27.4	35.1 - 35.3
November	26.0 - 28.5	35.2 - 35.3
December	26.0 - 29.0	35.2 - 35.4

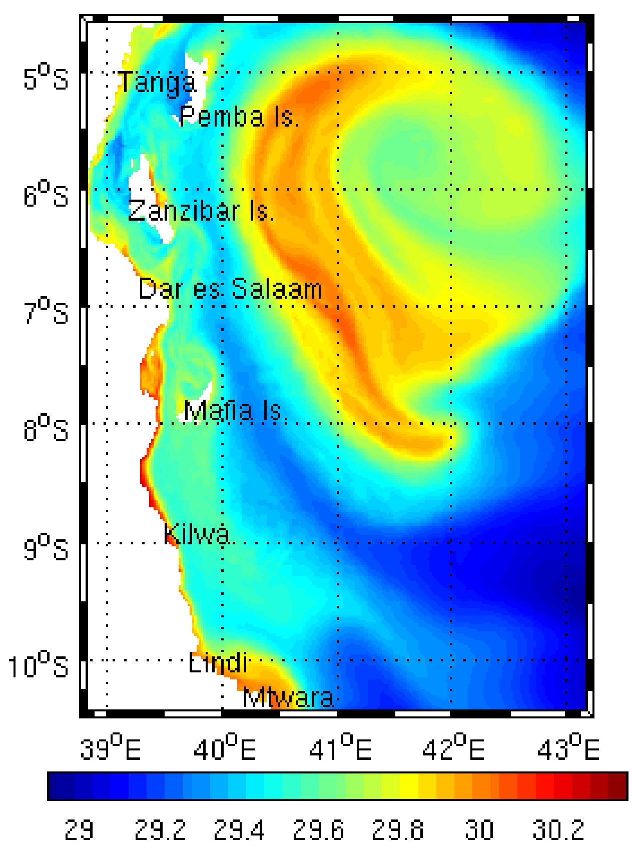

Figure 3. Sea surface temperatures (oC) during April representing the conditions during highest temperatures in a year (derived from the ROMS model).

in January and 8.5°S in July. Narrow streams of strong currents also flow northwards parallel to the coast in the Mafia, Zanzibar and Pemba Channels.

During the NE monsoon season, the general northward flow of the EACC turns east to form the ECC near the Equator. The generation of the ECC, which flows westwards, is associated with the formation of a cyclonic eddy between latitudes 5 and 6°S which shifts its position from west to east with season. In the south, a current develops near the coast below 9°S during the NE monsoon, forming a current that is directed southwards from Mafia Island to Mtwara (Figure 2). The southward current which starts developing in November, attains its peak in February and diminishes in April. The model results in the current study are consistent with *in-situ* measurements reported in previous studies along the coast of Tanzania, by Harvey (1977) and Iversen et al. (1984). However, the existence of the seasonal eddies along the coast of Tanzania have not been documented by any of the previous studies.

The average SST in the study area is about 27.5°C, ranging from a minimum of 25.0°C to a maximum of 30.2°C. Lower temperatures are generally experienced from July to October while relatively higher temperatures are experienced from December through May, almost coinciding with the NE and SE monsoon seasons, respectively, (Table 1). The lowest temperatures are observed in August (25.2 to 26.6°C) and September (25.0 to 26.6°C), while the highest temperatures are experienced in April (29.0 to 30.2°C) as shown in Table 1.

The general spatial distribution of surface temperatures along the coast during April is shown in Figure 3. Generally, the presented results from the ROMS model corroborated well with both the MODIS and the argo floats monthly climatologies (Figures 4 and 5, respectively), all showing that, the mean SST along the coast of Tanzania is between 28 and 30°C. The three datasets further show that, during April, the lowest SST along the coast of Tanzania are generally found on the shallow waters west of the continental shelf, while highest SST are found on the northeastern side of the Tanzanian coast.

The presented results are further consistent with the *in-situ* measurement results reported by previous investigators (Harvey, 1977) and by satellite derived measurements (Shaghude and Byfield, 2012) which also reported that, the highest and lowest temperatures along the coast of Tanzania are reported to be in March/April and August/September, respectively. The results are also similar to those of Newell (1957) and Iversen et al. (1984), who observed that, average SSTs range between 22 and 30°C. The present study has also observed that, during each season, the SSTs are particularly higher near the coast, especially in shallow estuaries and bays, and decrease further offshore. Other investigators such as Mahongo and Francis (submitted) also showed that, the average SST in this area during the period 2000 to 2009 was about 27.5°C, which is consistent with the

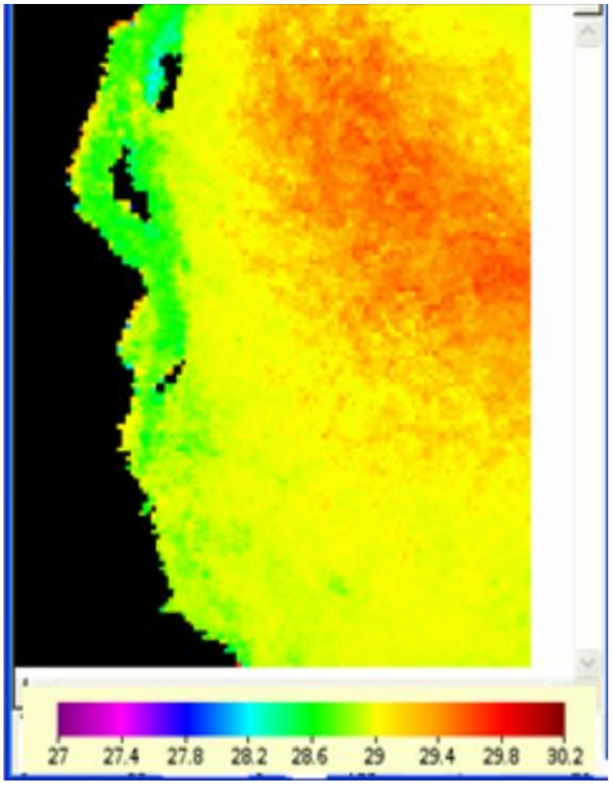

Figure 4. Sea surface temperatures (°C) during April representing the conditions during highest temperatures in a year (derived from MODIS data).

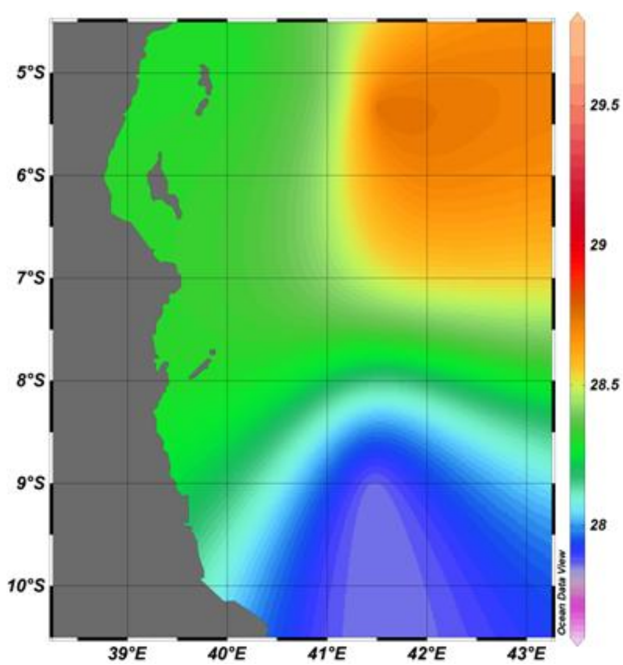

Figure 5. Sea surface temperatures (°C) during April representing the conditions during highest temperatures in a year (derived from the argo floats network data).

present model results. The authors utilized SST data extracted from HadISST1 monthly gridded global temperature data set (Rayner et al., 2003) at a location centred on 7.5°S and 39.5°E, which falls within the present study area.

Results from this study indicate that, the surface salinity has an average value of 35.1, varying between 34.5 and 35.5 (Table 1). The highest salinities are observed in December (35.2 to 35.4) and January (35.2 to 35.5), and lowest salinities are observed during May (34.7 to 35.1) and June (34.5 to 35.1) (Table 1). In contrast to the SST, the surface salinities are particularly lower in the inshore waters than in the offshore, especially within the estuaries and bays (Figure 6).

The lower salinities in the inshore waters could be attributed to the influence of fresh water introduced to the sea by the rivers/streams. Nevertheless, the salinity in the northern coastal offshore is relatively higher than the corresponding southern coast. The results on spatial salinity variation are again similar to those observed by Iversen et al. (1984), who noted that, the period of lowest salinities in the Tanzanian coastal waters coincide with the peak freshwater outflow. Another study by Bryceson (1982) noted that the salinity in coastal Tanzania start to decrease before the onset of the rains, attributing this to the advection of lower salinity water from the south.

The salinity and temperature profiles for a site positioned at 7.5°S and 42.5°E (plot not shown) indicates that, the salinity maximum in June is reached at a depth range of 100 to 200 m. The salinity then decreases rapidly up to a depth of 500 m, it increases slowly up to 1000 m before slowly decreasing to the minimum at the bottom depth. The temperature is almost constant in the first 50 m. It then decreases rapidly up to 300 m, then more slowly up to the minimum depth. These model results of salinity and temperature are similar to previous field observations (Harvey, 1977; Iversen et al., 1984).

Conclusions

This study is an appraisal of previous studies on the current dynamics along the coast of Tanzania, which were mainly based on patchy field observations, limited spatial extent and mainly focused on surface waters. In contrast, the present study has provided a broader understanding of the dynamics of the coastal waters along the entire coast of Tanzania (with the inclusion of the deep water dynamics) by configuring ROMS for the area.

The offshore dynamics which provide relevant information on offshore fishery resources such as tuna were scarcely known. In view of this, the results of the present study provides a better understanding to the policy and decision makers, particularly those who are dealing with fishery resource management on the

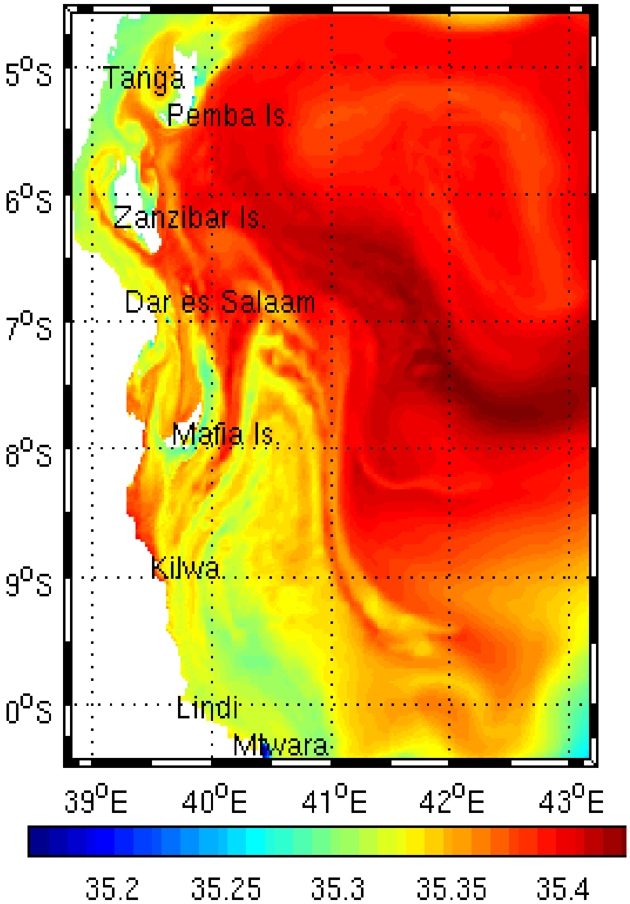

Figure 6. Sea surface salinities in December representing the conditions during highest salinities in a year.

physical environments of the Tanzanian deeper water habitats. Community available General Circulation Models (GCMs) such as the HYbrid Co-ordinate Ocean Model (HYCOM) have a resolution that does not resolve many features of the Tanzanian coastal zone such as the Mafia, Zanzibar and Pemba Channels, of extreme importance for the country.

The study also reveals that, the core of the EACC passes off and adjacent to the major islands of Pemba, Zanzibar, and Mafia, hence any plans to invest in offshore marine resource exploitation should take into account the seasonal changes of these waters. The model results provides further light on the dynamics along the navigational routes between Dar es Salaam/Zanzibar, Zanzibar/Pemba, and Tanga/Pemba, as experienced by boats plying between these ports. Occasionally, boats encounter increased turbulence in some routes especially during the SE Monsoons. A number of boats have consequently capsized over the recent past leading to enormous loss of human lives and properties.

Future modeling studies may incorporate surface fluxes from NCEP reanalysis for inter-annual simulations, tidal data from the Oregon State University global models of ocean tides (Egbert and Erofeeva, 2002), and the discharge from major rivers. Nesting with higher resolution bathymetry may also be used in areas of strategic importance such as in the continental shelf and around islands.

ACKNOWLEDGEMENTS

This study was supported by the International START Secretariat with funds supplied by the U.S. Global Change Research Program, and administered by the U.S. National Science Foundation under Grant Number GEO-0627839. POGO-SCOR and WIOMSA fellowship programs provided initial funding support for the training in ROMS. Prof. F. Shillington and Dr. I. Hallo of the University of Cape Town and Dr. J. Zavala-Garay of Rutgers University are gratefully acknowledged for hosting of the first author during fellowship placements at the respective universities.

ABBREVIATIONS

EACC, East African coastal current; **ERDDAP,** environmental research division's data access program; **MODIS,** moderate resolution imaging spectroradiometer; **NE,** Northeast; **NOAA,** national oceanic and atmospheric administration (US); **ROMS,** regional ocean modelling system; **SE,** southeast; **SEC,** south equatorial current.

REFERENCES

Bryceson I (1982). Seasonality of oceanographic conditions and phytoplankton in Dar es Salaam waters. Univ. Sci. J. (University of Dar es Salaam) 8:66-76.

Casey KS, Cornillon P (1999). A comparison of satellite and in situ based sea surface temperature climatologies. J. Clim. 12:1848-1863.

Conkright ME, Locarnini RA, Garcia HE, O Brien TD, Boyer TP, Stephens C, Antonov JI (2002). World Ocean Atlas 2001: Objective Analyses, Data Statistics, and Figures CD-ROM Documentation. National Oceanographic Data Center, Silver Spring, MD, P. 17.

Da Silva AM, Young CC, Levitus S (1994). Atlas of surface marine data 1994, Vol. 1, algorithms and procedures NOAA Atlas NESDIS 6. U. S. Department of Commerce, NOAA, NESDIS, USA, P. 74.

Egbert G, Erofeeva S (2002). Efficient inverse modeling of barotropic ocean tides. J. Atmos. Oceanic Technol. 19:183-204.

FAO/UNEP (1982). Marine pollution in the East African Region. UNEP Reg. Seas Rep. Stud. 8:54.

Garcia-Reyes M, Mayorga-Adame G, Moulton MR, Nadeau PC (2009). Modeling of the Zanzibar Channel, IMS, Zanzibar, P. 27.

Harvey J (1977). Some aspects of the hydrography of the water off the coast of Tanzania: A contribution to CINCWIO. Univ. Sci. J. (University of Dar es Salaam) 3:53-92.

Hermes JC, Reason CJC (2008). Annual cycle of the South Indian Ocean (Seychelles-Chagos) thermocline ridge in a regional ocean model. J. Geophys. Res. 113(C4):C04035.

Iversen SA, Myklevoll S, Lwiza K, Yonazi J (1984). Tanzanian Marine fish Resources as investigated by Dr. Fridtjof Nansen Research Vessel. The Proceedings of the NORAD-Tanzania Seminar,

Mbegani, Tanzania. P. 186.
Liu WT, Tang W, Polito PS (1998). NASA scatterometer global ocean-surface wind fields with more structures than numerical weather prediction. Geophys. Res. Lett. 25:761-764.
Mahongo SB, Francis J, Osima SE (2012). Wind Patterns of Coastal Tanzania: Their Variability and Trends. Western Indian Ocean J. Mar. Sci. 10:107-120.
Mayorga-Adame CG (2007). Ocean Circulation of the Zanzibar Channel: A Modeling Approach, IMS, Zanzibar, P. 8.
McClanahan T (1988). Seasonality in East Africa's coastal waters. Mar. Ecol. Prog. Ser. 44:191-199.
Newell BS (1957). A preliminary survey of the hydrography of the British East African Coastal Waters.Col. Off. Fish. Pubs. Lond. 9:1-21.
Newell BS (1959). The hydrography of British East African coastal waters.Col. Off. Fish. Pubs. Lond.12:1-18.
Nyandwi N, Dubi AM (2001). Episodic atmospheric changes and their impact on the hydrography of the coastal waters of Tanzania. Clim. Res. 18:157-162.
Penven P, Cambon G, Tan TA, Marchesiello P, Debreu L (2010). ROMS AGRIF / ROMSTOOLS User's Guide, Inst. De Rech. Pour le Dev.(IRD), Marseille, France, P. 91.
Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. J. Geophys. Res. 108(D14):4407.
Shaghude YW, Byfield V (2012). Using sea surface temperature to assess coral bleaching risk. In: Maathuis BHP, Mannaerts CMM (eds) GEONETCast DevCoCast application manual, version 1. University of Twente, Enschede, The Netherlands, pp. 179-194.
Shchepetkin AF, McWilliams JC (2005). The regional oceanic modelling system (ROMS): A split-explicit, free-surface, topography-following-coordinate oceanic model. Ocean Model. 9:347-404.
Swallow JC, Schott F, Fieux M (1991). Structure and transport of the East African Coastal Current. J. Geophys. Res. 96:2254-2267.
Warren B, Stommel H, Swallow JC (1966). Water masses and patterns of flow in the Somali basin during the southwest monsoon of 1964. Deep-Sea Res. 13:825-860.
Wilkin JL, Arango HG, Haidvogel DB, Lichtenwalner CS, Durski SM, Hedstrom KS (2005). A regional Ocean Modeling System for the Long-term Ecosystem Observatory. J. Geophys. Res. 110 (C06S91).