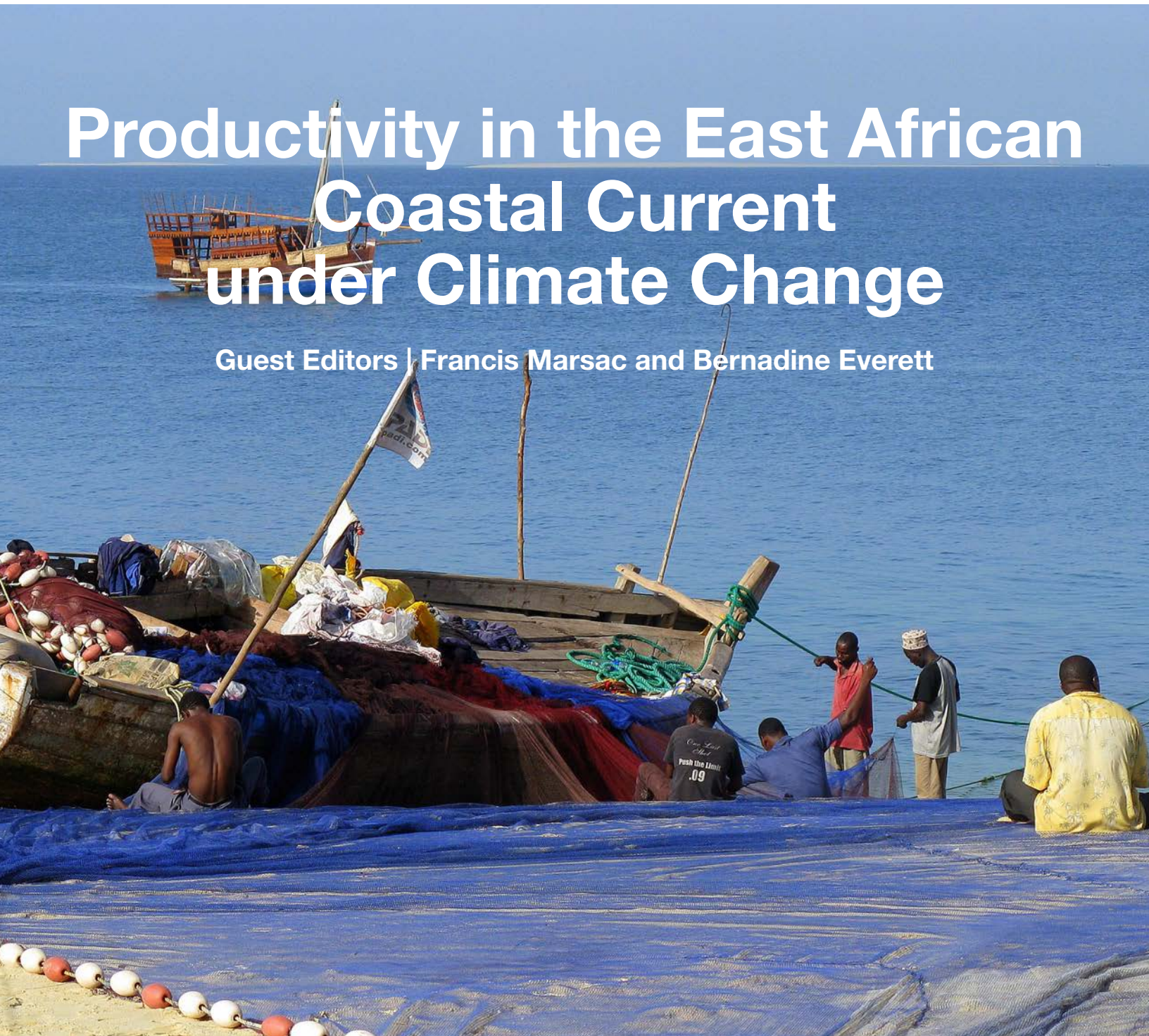


Western Indian Ocean JOURNAL OF Marine Science

Special Issue 1/2020 | Dec 2020 | ISSN: 0856-860X

Productivity in the East African Coastal Current under Climate Change

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ISSN 0856-860X



A comparative study of ocean surface interannual variability in Northern Tanzania and the Northern Kenya Bank

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Abstract

The livelihoods of most residents of Tanga (Northern Tanzania) and Malindi (Northern Kenya), rely strongly on fishing activities in the East African shelf region. Thus, understanding variations in sea surface temperature (SST) and its related parameters such as thermocline depths and upper ocean circulation are crucial. This study applies a regional model to understand interannual spatial relationships between ocean circulation and SST off Northern Tanzania and on the Northern Kenya Bank. The results indicate slight differences in variations off the Northern Tanzanian shelf region and the Northern Kenya Bank. Such small variations might have local impacts on the human population through influencing primary productivity and fisheries. The coastal waters off Malindi indicate stronger variations, particularly in 1997 (cold SST) and 1998 (warm SST), than those off Tanga region. The SST anomalies seem to be associated with thermocline and sea surface height (SSH) off Malindi, while off Tanga they relate only to SSH. This information provides further understanding of parameters that may affect fishing activities in these regions and can be used for planning and management processes.

Keywords: El Niño-Southern oscillation, El Niño, La Niña, Ocean off East Africa, Thermocline

Introduction

Impacts of interannual variability of meteorological and oceanic characteristics on a region depend on the pre-existing climate and local characteristics of a particular region (Marchant *et al.*, 2006). Such impacts have been reported to be associated with variability of SST, precipitation and sea level pressures during different El Niño-Southern Oscillation (ENSO) events (e.g. Reason *et al.*, 2000; Liu and Alexander, 2007; Schott *et al.*, 2009). During an El Niño event, the tropical Indian Ocean warms and consequently enhances precipitation in equatorial East Africa mainly during October-December following the first warming in the Pacific. Such enhanced precipitation leads to severe

flooding in parts of East Africa (Schott *et al.*, 2009). Roughly the reverse occurs during a La Niña event, when the ocean off East Africa cools and consequently reduces precipitation in equatorial East Africa, again mainly during the October-December short rain season. Furthermore, the warm SST anomalies in 1997/1998 negatively affected coral reefs by increasing the level of coral mortality to about 50-60 % (Obura *et al.*, 2002). The impacts are stronger when the ENSO events co-occur with the climate mode in the Indian Ocean known as the Indian Ocean dipole (IOD). A good example of this scenario is the positive IOD and/or El Niño events in 1997/1998 that led to severe floods in parts of East Africa (Schott *et al.*, 2009).

Fishing is the main food source and commercial activity in the coastal communities of Tanzania contributing about 2.1-5.0 % of the Gross Domestic Product (GDP) of Mainland Tanzania and 2.2-10.4 % for Zanzibar (Jiddawi and Öhman, 2002). However, this important activity is affected by interannual variability in the oceanographic and meteorological conditions in the region, which ultimately lead to impacts on socio-economic activities in the coastal communities (Obura *et al.*, 2002; Yamagata *et al.*, 2003, 2004; Schott *et al.*, 2009).

Materials and methods

Model description and configuration

This study applies the Regional Oceanic Modeling System (ROMS) to simulate the ocean off the East African coast. Different authors have demonstrated and proved that ROMS realistically simulates the tropical Indian Ocean region (e.g. Hermes and Reason, 2008; Penven *et al.*, 2006; Manyilizu *et al.*, 2014, 2015, 2016; Collins *et al.*, 2014). The model is a free-surface, terrain-following ocean model which solves the three dimensional hydrostatic

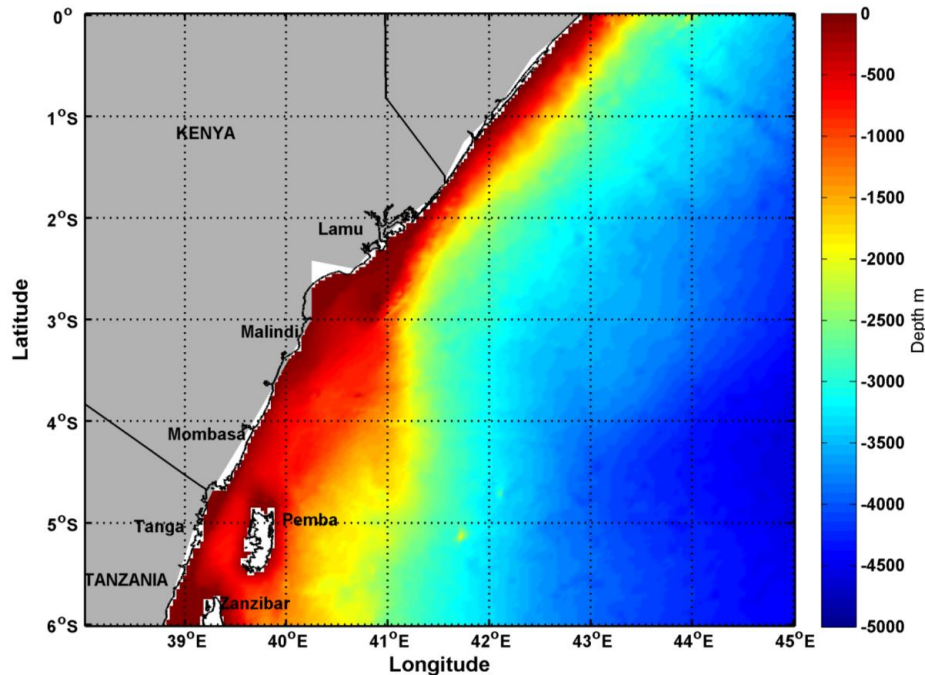


Figure 1. Coastal ocean with bathymetry off Tanga in Northern Tanzania and Malindi on the Northern Kenya Bank.

The majority of studies in East African coastal waters (e.g. Mayorga-Adame, 2007) have not included models to enhance and improve the understanding and knowledge of SST and ocean circulation. This research applies an ocean model to better understand these relationships in the shelf region off this coast. The location and bathymetry patterns of the ocean off Tanga and Malindi are portrayed in Figure 1.

The study aimed to compare variability of inter-annual ocean surface parameters off Northern Tanzania and the Northern Kenya Bank. The study attempts to address the following questions: How does upper ocean circulation and SST in the ocean off Northern Tanzania and the Northern Kenya Bank evolve inter-annually?; and, How does such spatial and temporal evolution relate to each other?

primitive equations (Shchepetkin and McWilliams, 2003, 2005). The vertical structure is discretized in stretched, terrain-following coordinates, and orthogonal curvilinear coordinates are applied in the horizontal structure on a staggered Arakawa C-grid. The K-Profile Parameterization (KPP) provides the model vertical mixing (Large *et al.* 1994). This research uses the IRD version of the code (ROMS AGRIF), available from the Website <http://www.romsagrif.org> (Debreu *et al.*, 2012).

The study adapted the model configuration used in Manyilizu *et al.* (2014, 2016) which was configured in the tropical western Indian Ocean for the domain 37.5-60°E and 4.85°N-18°S with its bathymetry derived from ETOPO2V2C (see www.ngdc.noaa.gov). The model uses a global topography dataset

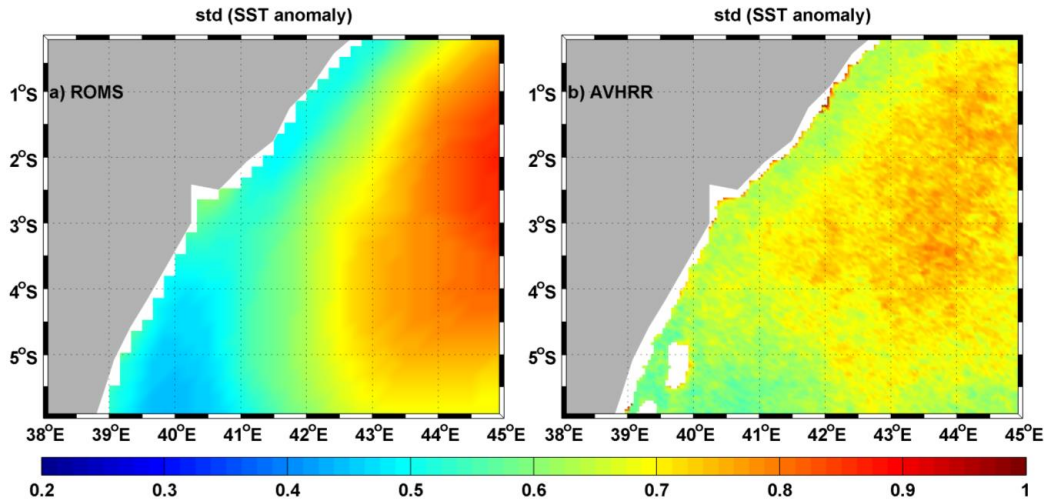


Figure 2. Standard deviation of the monthly SST anomalies off Tanga in Northern Tanzania and off Malindi on the Northern Kenya Bank.

at 2' resolution processed by Smith and Sandwell (1997). This run is an inter-annual simulation, forced from 1978 to 2007 by the National Center for Environmental Prediction (NCEP) reanalysis-2 of winds and heat fluxes with two years spin-up time. The model simulation has 40 vertical levels, 1/6° horizontal resolution and time steps of 1800s. The model outputs are averaged every two model days which in turn are processed to calculate monthly and climatological data.

Datasets

The ROMS model was used to conduct a comparative study of ocean surface interannual variability in Northern Tanzania (Tanga) and the Northern Kenya

Bank (Malindi). For validation, the model outputs were compared with observations and satellite data. The SST data from the Advanced Very High Radiometer Resolution (AVHRR) Pathfinder version 5 at 4 km horizontal resolution (<ftp://ftp.nodc.noaa.gov/pub/data.nodc/pathfinder>) were used for validation of the model SST for the same region from 1982 to 2007. Furthermore, the validation of the ROMS model was provided by the altimeter sea surface height (SSH) observations from Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO). These data are currently hosted by the French institution, National Centre for Spatial Studies (CNES), and freely distributed on-line via Copernicus Marine Services (<http://marine.copernicus.eu/>). The altimeter sea surface

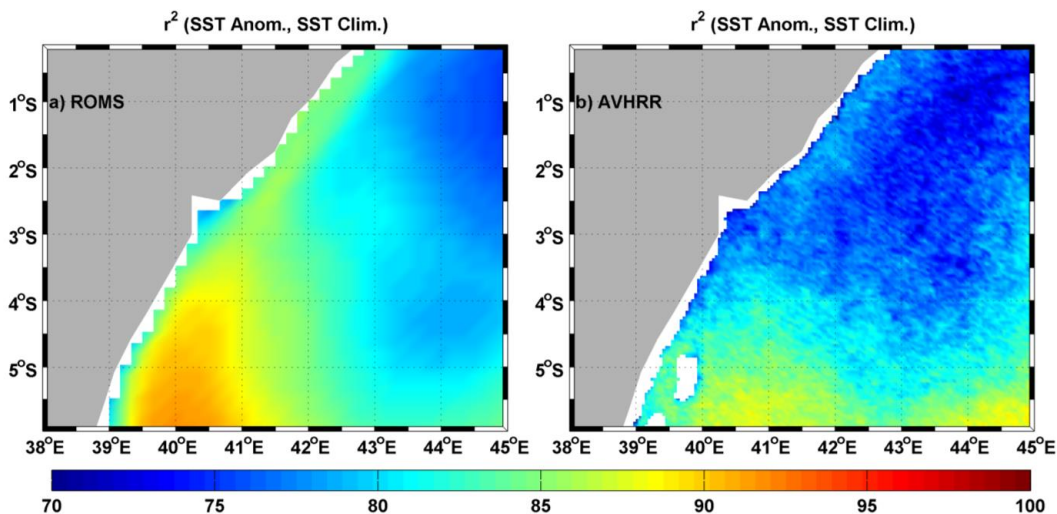


Figure 3. Correlation coefficient squared (r^2) of the monthly SST anomalies in the coastal ocean off Tanga in Northern Tanzania from averaged box with 4.5-5.5°S and 39-39.5°E with the entire East African coastal waters for a) ROMS model and b) AVHRR data.

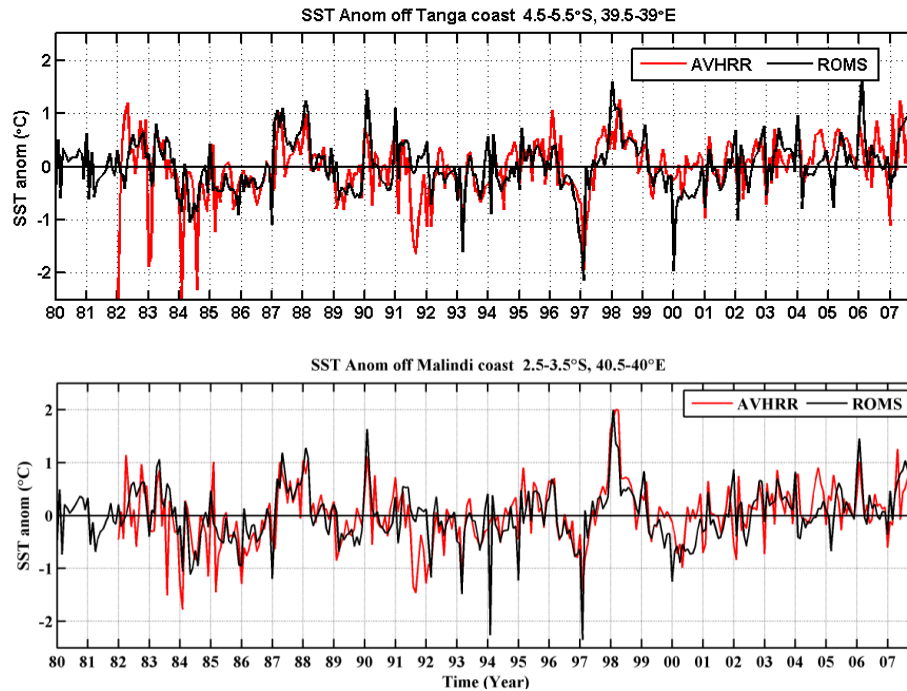


Figure 4. SST time-series of SST off Tanga coast (top panel) and Malindi coast (bottom panel).

height observations for AVISO were obtained for 1992 to 2007 at $1/3^\circ$ resolution. These are gridded data which combine altimeter measurements from different satellites by an interpolation mapping technique (Ducet *et al.*, 2000). This study used gridded maps of absolute dynamic topography.

Results and discussion

SST standard deviation and shared variances

Figure 2a and b indicate relatively weaker interannual variations in SST of the coastal waters off Tanga than that off Malindi in both model and satellite data. The relative weak SST variations off Tanga cover

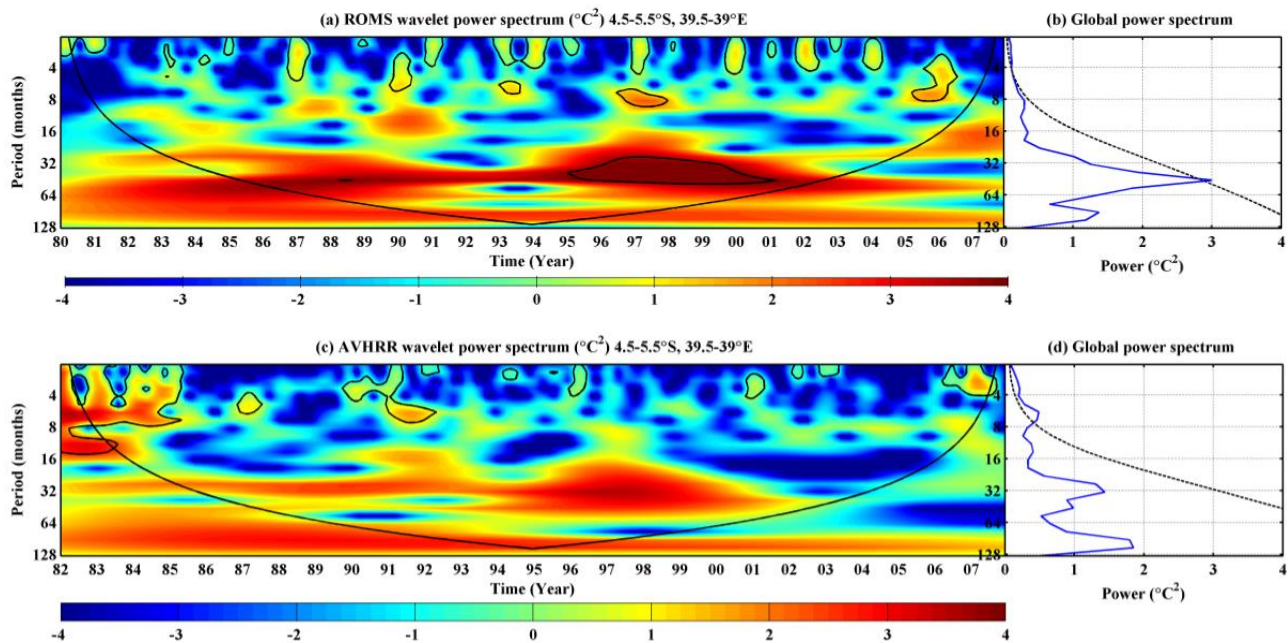


Figure 5. Wavelet power spectrum (left column) and power of the wavelet analysis (right column; blue line) of the box-averaged monthly SST anomalies off Tanga coast from the model (a and b) and AVHRR (c and d) in the Northern Tanzanian shelf region. The cone of influence is shown as a thin black line, as well as contours that indicate the 95 % confidence level. Significance in the global wavelet spectrum is indicated by the black dashed line.

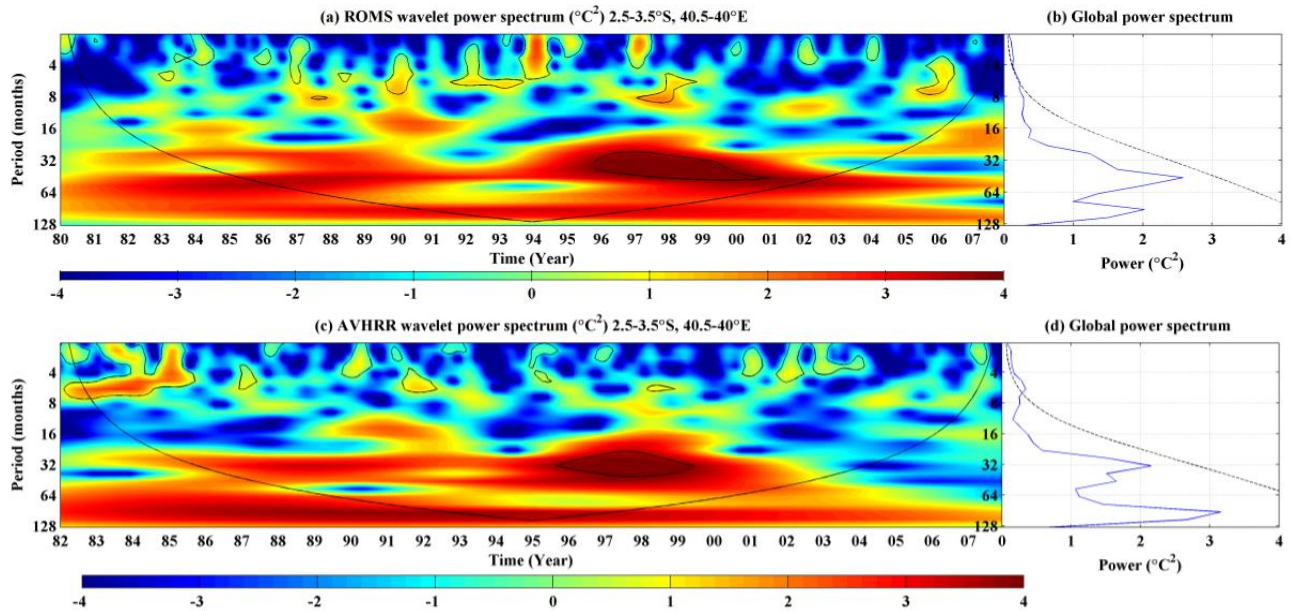


Figure 6. Wavelet power spectrum (left column) and power of the wavelet analysis (right column; blue line) of the box-averaged monthly SST anomalies off the Malindi coast from the model (a and b) and AVHRR (c and d) in the Northern Kenya Bank region. The cone of influence is shown as a thin black line, as well as contours that indicate the 95 % confidence level. Significance in the global wavelet spectrum is indicated by the black dashed line.

a broader zonal region than in Malindi. These results suggested weaker variations in the waters off Tanga. To check the origin of the weakest interannual variations of SST off the Tanga shelf region, shared variance was established between the waters of the Tanga shelf (4.5°S to 5.5°S and 39°E to 39.5°E) and those in the rest of the domain (0° to 6°S and 38°E to 45°E). The shared variance of the coastal waters off Tanga with the rest of the East African coastal ocean is presented in Figure 3a and b for the ROMS model and AVHRR data, respectively. Such SST variations were reflected in shared variance although there is a relatively small difference with that in the Malindi region. There were relatively higher variations of SST in the coastal waters off Malindi than those off Tanga. Such variations appeared to be confined close to the coast.

Time series and wavelet analysis

Figure 4 displays time-series of SST anomalies in the waters off the Tanga (top panel) and Malindi coast (bottom panel) from both the ROMS model and AVHRR satellite data. Weak variations of SST were evident in the waters off Tanga compared to those off Malindi. Significantly warm SST appeared in 1998 in both regions with warmer waters (about 2.0 °C) evident off Malindi than off Tanga (about 1.2 °C) in that year. However, cooler waters (about 2.5°C) were apparent off Malindi compared to about 2.1°C off Tanga. Thus, there were stronger SST variations off the Malindi coast than off the Tanga coast.

Figure 5 and 6 show wavelet analyses which determine the differences in time and frequency of the SST variability in Tanga and Malindi coastal waters. The global power spectrum (GPS) displayed a significant intermediate maximum at 6 months for AVHRR and between 0-4 months for ROMS. Furthermore, the GPS at 6 months does not appear to express a stronger signal in Malindi compared to Tanga. The peak was at 48 months in both Tanga and Malindi for ROMS, while the peak was at 32 months in Malindi from the AVHRR dataset. It should be noted that the significant signal at 32 and 48 months occurs only during a few years (1996-1999) surrounding the strong 1997-1998 El Niño event. During those years, the signal was stronger off Malindi compared to Tanga.

Relationship between SST, 20 °C isothermal depth and SSH anomalies

Figure 7 and 8 display Hovmöller plots of SST, the 20 °C isothermal depth and sea surface height anomalies for Tanga and Malindi, respectively. Warm SST anomalies in both locations indicated episodes of strong warming from east to west in 1981, 1983, 1987-88, 1998 and 2006 which were ENSO years. Such warm episodes were reflected with positive anomalies of thermocline depths and sea surface height. Variations in the 20 °C isothermal depth was evident comparing to that of SSH anomalies. Deep 20 °C isothermal depth was associated with SSH rise, but the pattern of continuous deep 20 °C isothermal depth from 1994

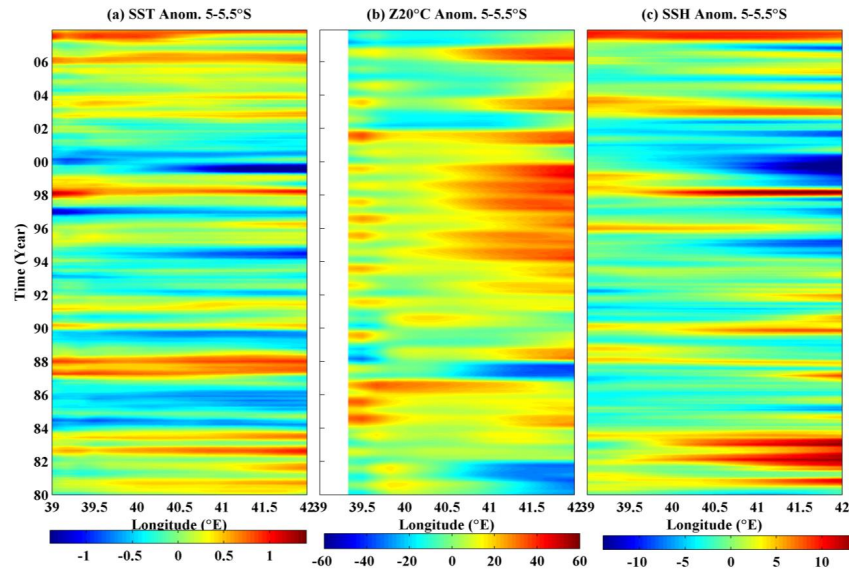


Figure 7. Hovmöller plots for ROMS results in the Tanga shelf region from the coast (39°E to 42°E) for monthly anomalies averaged over 5.5–5°S of (a) SST in °C (b) Z20 °C in M and (c) SSH in M from satellite altimetry data.

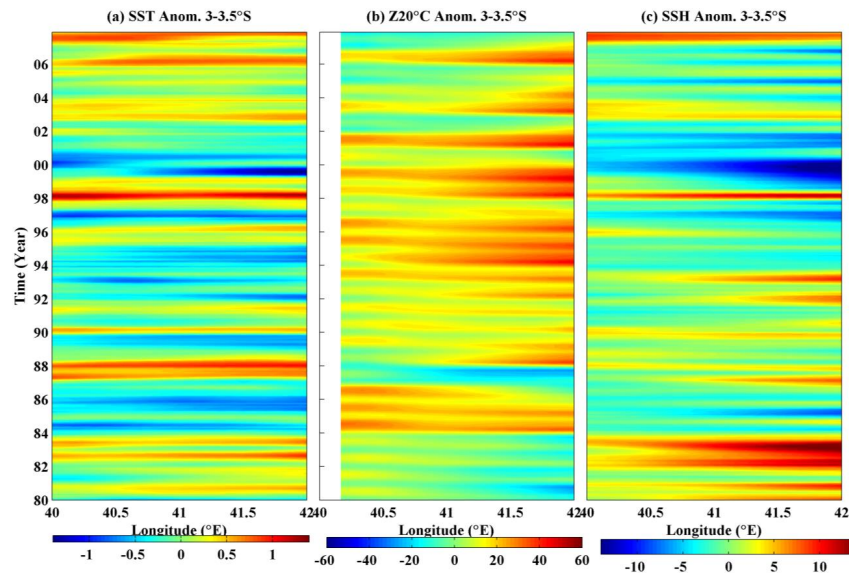


Figure 8. Hovmöller plots for ROMS results in the Malindi shelf region from the coast (40°E to 42°E) for monthly anomalies averaged over 3.5–3°S of (a) SST in °C (b) Z20 °C in M and (c) SSH in M from satellite altimetry data.

to 2000 when the SSH varied significantly, is unexplained. Such SST variations can be associated with a rise of SSH which leads to an increase of heat content in water column. Modelled cold SST anomalies off the Tanga coast in 1984, 1986, 1989, 1993–94, 1997 and 1999–2000 matches with negative SSH anomalies. Thus, lowered SSH variations lead to a decrease in heat content and consequently, lower SST anomalies. Overall, the signals modelled and observed off Malindi were stronger than those off Tanga.

The Hovmöller plots off Tanga coast in the Northern Tanzanian shelf region and that in the Northern Kenya Bank off the Malindi coast indicated slight variations. The coastal waters off Malindi indicated stronger variations, particularly in 1997 (cold SST) and 1998 (warm SST), as compared to that off Tanga region.

Conclusion and recommendations

The East African coast experiences interannual variability of parameters involved in air-sea interactions

and ocean dynamics. The main activities for the majority of coastal residents in Tanga in Northern Tanzania and Malindi on the north coast of Kenya rely on fishing activity in the East African shelf region. Understanding variations of SST and its related parameters such as the depth of the 20 °C isotherm can provide useful information to fisheries scientists and managers. This study uses a regional ocean model to address the temporal-spatial variations of SST and the related parameters in coastal waters off Tanga and Malindi. The coastal waters off Malindi indicate slightly stronger variations in SST, 20 °C isothermal depth and SSH as compared to those offshore of Tanga region, especially in 1997 (cold SST) and 1998 (warm SST). Off Malindi, the SST anomalies seem to be associated with changes in thermocline and SSH while those off Tanga relate to only SSH. Such small variations might have local impacts to the human population by affecting primary production and associated distribution and abundance of fisheries resources. However, this is not addressed in this study. This analysis provides an understanding of seasonal variations induced by the ENSO off the coast of East Africa, which might be useful for planning climate sensitive activities in the region.

Acknowledgments: Financial support was provided through the project on 'Responses of Biological Productivity and Fisheries to Changes in Atmospheric and Oceanographic Conditions in the Upwelling Region Associated with the East African Coastal Current' sponsored by WIOMSA and IOC-UNESCO.

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