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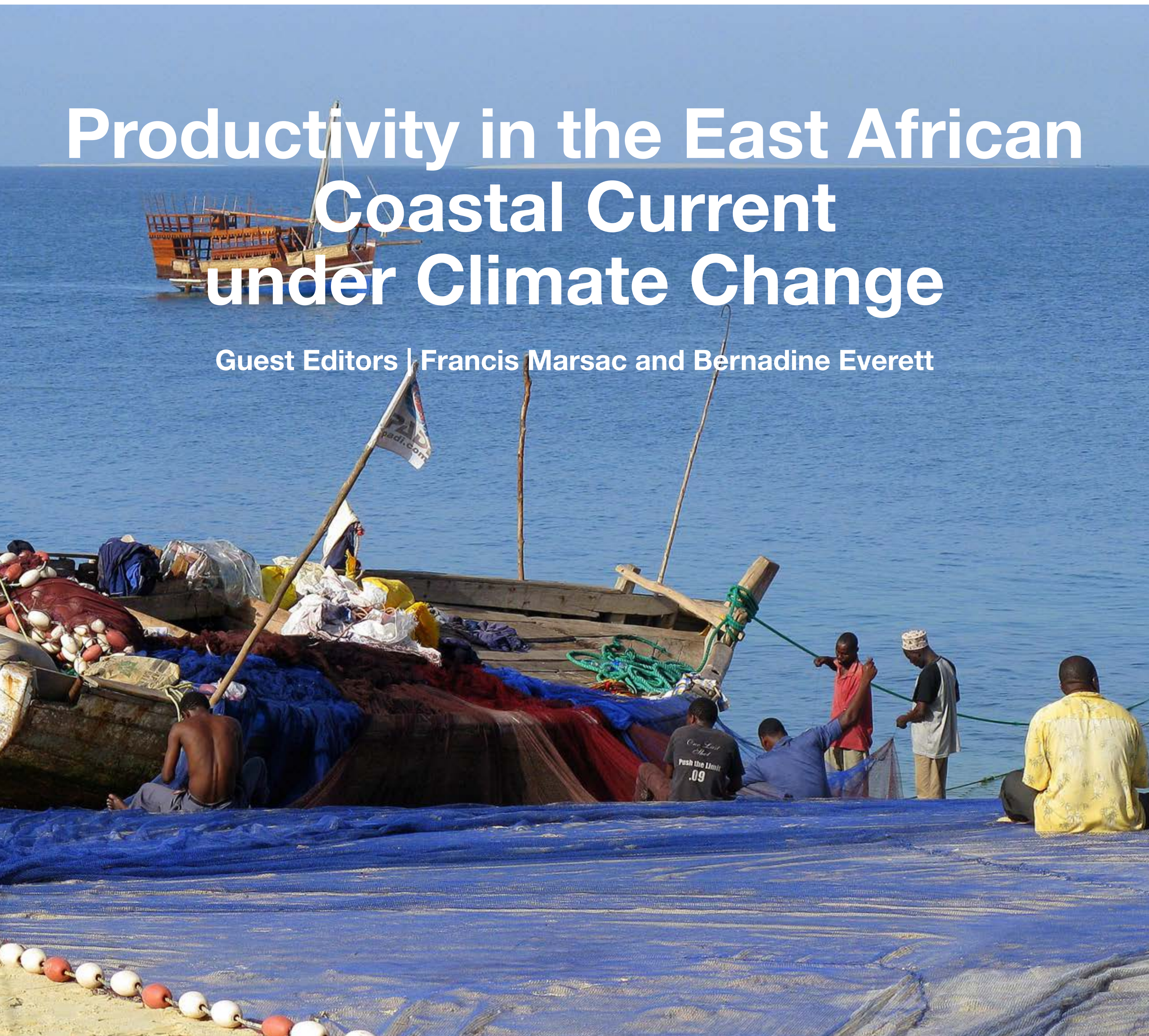
# Productivity in the East African Coastal Current under Climate Change

Guest Editors | Francis Marsac and Bernadine Everett



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# Editorial Note
# Productivity in the East African Coastal Current under Climate Change

This special issue is the result of the work from the Productivity in the East African Coastal Current under Climate Change (PEACC) Project. The PEACC Project (July 2016 - June 2018) aligned with the Western Indian Ocean Upwelling Research Initiative (WIOURI), one of the flagship initiatives under the Second International Indian Ocean Expedition (IIOE-2: 2015 to 2020). The goal of IIOE-2 is to advance our understanding of the Indian Ocean and its role in the Earth System in order to enable informed decisions in support of sustainable development and the well-being of humankind. The PEACC Project was endorsed by the IIOE-2 in March 2018 (Endorsement No. IIOE2-EP28), in recognition of its potential for contributing to an increased multi-disciplinary understanding of the dynamics of the Indian Ocean, and of its contribution to the achievement of societal objectives within the realm of the Indian Ocean region.

The project was undertaken by a multidisciplinary team of scientists from Tanzania, Kenya, South Africa, United Kingdom and United States of America, representing a consortium of ten institutions led by the Tanzania Fisheries Research Institute (TAFIRI). The project was largely supported by the Western Indian Ocean Marine Science Association (WIOMSA), with partial contributions from the UNESCO/IOC Sub-commission for Africa and the Adjacent Island States, Nairobi. The later supported the convening of two project planning and harmonization meetings in Kenya and Tanzania, respectively.

The objective of this project was to investigate the responses of biological productivity and fisheries to changes in atmospheric and oceanographic conditions in the upwelling region associated with the East African Coastal Current. The hypothesis was that coastal upwelling is often associated with increased productivity of both primary producers and small pelagic fishes. Conversely, the small pelagic fishes, which have in the recent past constituted the main source of protein supply to coastal communities along the East African coastal region, have been facing persistent fishing pressure. The preference for small pelagic fishes was triggered by the previously preferred demersal and reef fisheries catches declining due to overfishing and the use of destructive fishing methods.

The focus of the PEACC Project was on two case study sites: The Pemba Channel in Tanzania, and the North Kenya Bank in Kenya. The project goal was to provide management action points to enhance coastal community resilience to vulnerability associated with climatic changes. The various articles in this special issue bring together the most current information on four major topics: primary productivity, fisheries ecology, biophysical modeling and climate, as well as socio-economics.

Under **primary productivity**, the first article by Kamau *et al*. investigated the factors influencing spatial patterns in Kenyan territorial waters. Primary productivity was found to be largely supported by an upwelling phenomenon and organic matter mineralization. In another paper, Kamau *et al*. employed multivariate analysis to determine the productivity drivers in the same area. This second paper by Kamau *et al* strengthens the conclusions of the previous paper on the region's productivity. Using Principal Component Analysis in the Pemba Channel, Kyewalyanga *et al*. concluded that Chl-a concentration was significantly higher during the northeast monsoon, as compared to the southeast monsoon period, and this difference has been linked to higher nutrient concentrations during the northeast season, most probably due to seasonal upwelling in the area.

Under **fisheries ecology**, Kamukuru *et al*. investigated the age, growth and mortality of the anchovy *Stolephorus commersonnii* caught off the coast of Tanga, Tanzania. Results indicate an overfishing scenario which requires management intervention. Sululu *et al*. assessed the reproductive biology of this anchovy, as well as the spotted sardine (*Amblygaster sirm*). Both species exhibited protracted spawning seasons and skewed size dependent sex ratios with females predominating in larger size classes. Additionally, Sekadende *et al*. contributed on the food and feeding dynamics of *S. commersonnii* and the mackerel *Rastrelliger kanagurta*. The study revealed the importance of shrimps as food for *S. commersonnii*. It further showed that *S. commersonnii* are important items in the diet of *R. kanagurta* and the two species occupy the same niche.

Under **biophysical modeling and climate**, Manyilizu *et al.* analyzed the inter-annual relationship of sea surface temperature (SST) and upper-ocean circulation between northern Tanzania and the North Kenya Bank, and concluded that there was a slight difference in variations between the two study areas. Halo *et al*. developed a coupled physical-biophysical model to investigate the circulation and coastal upwelling along the Tanzanian and Kenyan coasts, and concluded that the coastal upwelling in this region is a normal occurrence, but with high levels of spatial and temporal variability, where the strongest events are small localized cells that develops in the Pemba Channel. Garcia-Reyes *et al*. studied the present and future trends in winds and SST along the East African coast under climate change. The authors observed that coastal areas have experienced and will continue to experience warming of their surface waters, but at lesser rates than the rest of the WIO region. Winds show consistent future decreasing trends during the NE monsoon, whereas this is not clearly demonstrated during the southeast monsoon. The northeast monsoon trend in wind might be associated with the higher SST trend observed in this region.

Under **socio-economics**, Ochiewo *et al*. investigated the livelihood impacts and adaptation in fishing practices as a response to recent climatic changes on the North Kenya Bank. A combination of climate change and increased fishing effort has caused a decline in the catches and changes in the fish species composition, while climatic changes have increased the vulnerability of the fishing communities. Lastly, Mwaipopo and Mahongo investigated the adaptive capacity of small pelagic fishing communities in Tanga (Tanzania) to changes in climate-related phenomena. The study illustrated how conditions associated with upwelling, while not readily obvious to fishers, matches some of their fishing strategies, with implications to their fisheries-dependent livelihoods. Yet, fishers' perceptions on factors influencing changes in the fisheries are a key in determining the response options they adopt.

The hypothesis that coastal upwelling is often associated with increased productivity of both primary producers and small pelagic fishes has been confirmed in this project where small pelagic catches and nutrient concentrations were on average higher during the northeast monsoon (associated with seasonal upwelling) than during the southeast monsoon. These findings are expected to improve our understanding of relationships between changes in climate, interacting with the ocean and other drivers, on biological productivity and fisheries, and how climate exacerbates environmental stressors and impacts ecological processes sustaining small pelagic fish stocks in the upwelling region associated with the EACC. Through the PEACC Project, new scientific knowledge has been generated and presented in this issue that will better inform policy and decision making for improved management and governance of small pelagic fisheries resources. Lastly, the PEACC project has provided valuable baseline data and information that can be utilized in future related research.

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# 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).

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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 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).

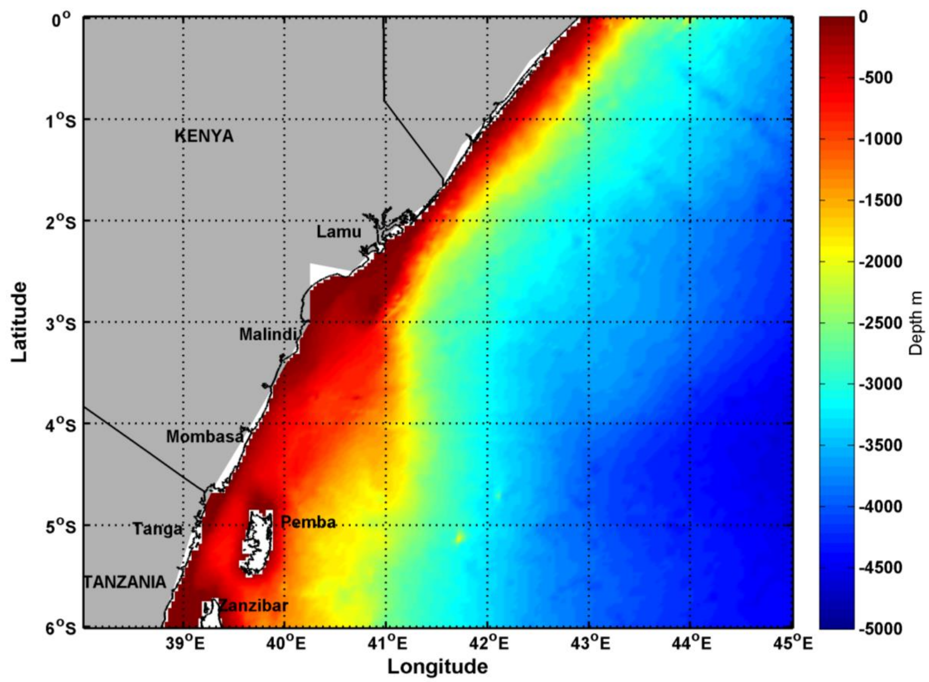


**Figure 1.** Coastal ocean with bathymetry off Tanga in Northern Tanzania and Malindi on the Northern Kenya Bank.

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?

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

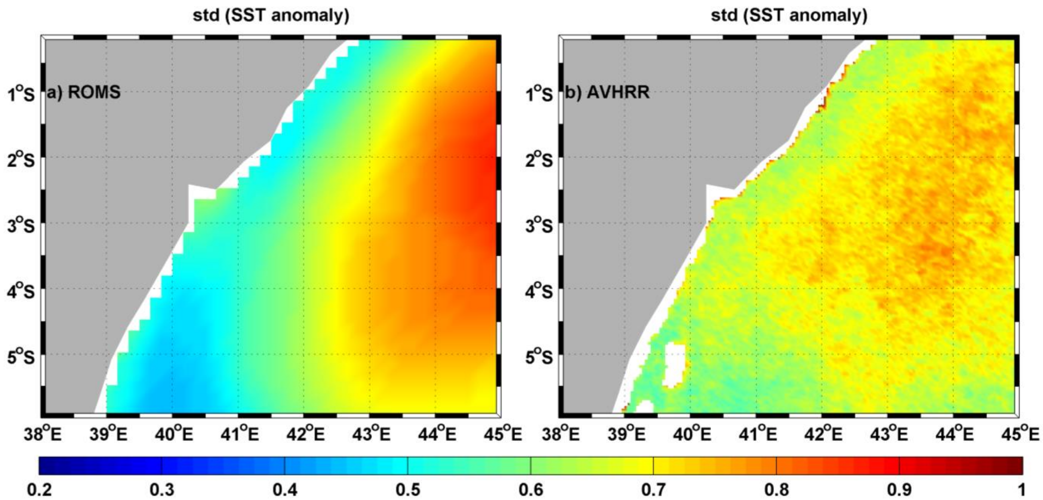


**Figure 2.** Standard deviation of the monthly SST anomalies off Tanga in Northern Tanzania and off Malindi on the Northern Kenya Bank.

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:192 //marine.copernicus.eu/). The altimeter sea surface

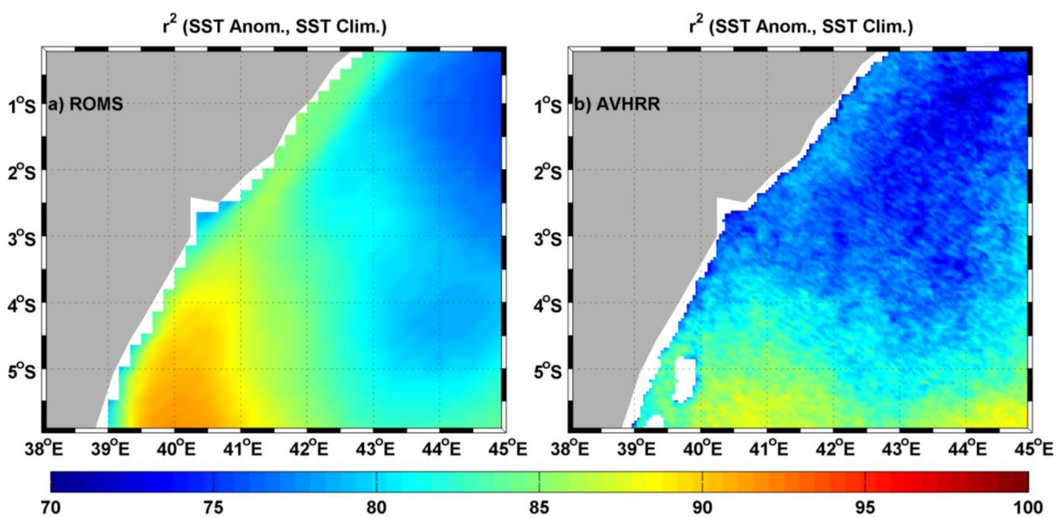


**Figure 3.** Correlation coefficient squared ($r^2$) of the monthly SST anomalies in the coastal ocean off Tanga in Northern Tanzania from averaged box with 4.5-5.5°S and 39-39.5°E with the entire East African coastal waters for a) ROMS model and b) AVHRR data.

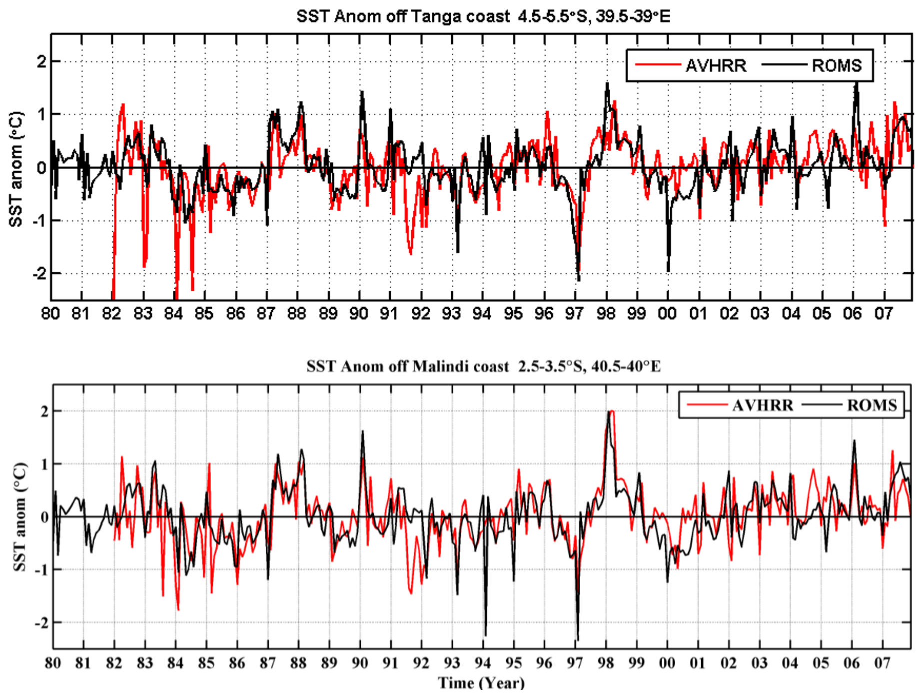


**Figure 4.** SST time-series of SST off Tanga coast (top panel) and Malindi coast (bottom panel).

height observations for AVISO were obtained for 1992 to 2007 at 1/3° 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

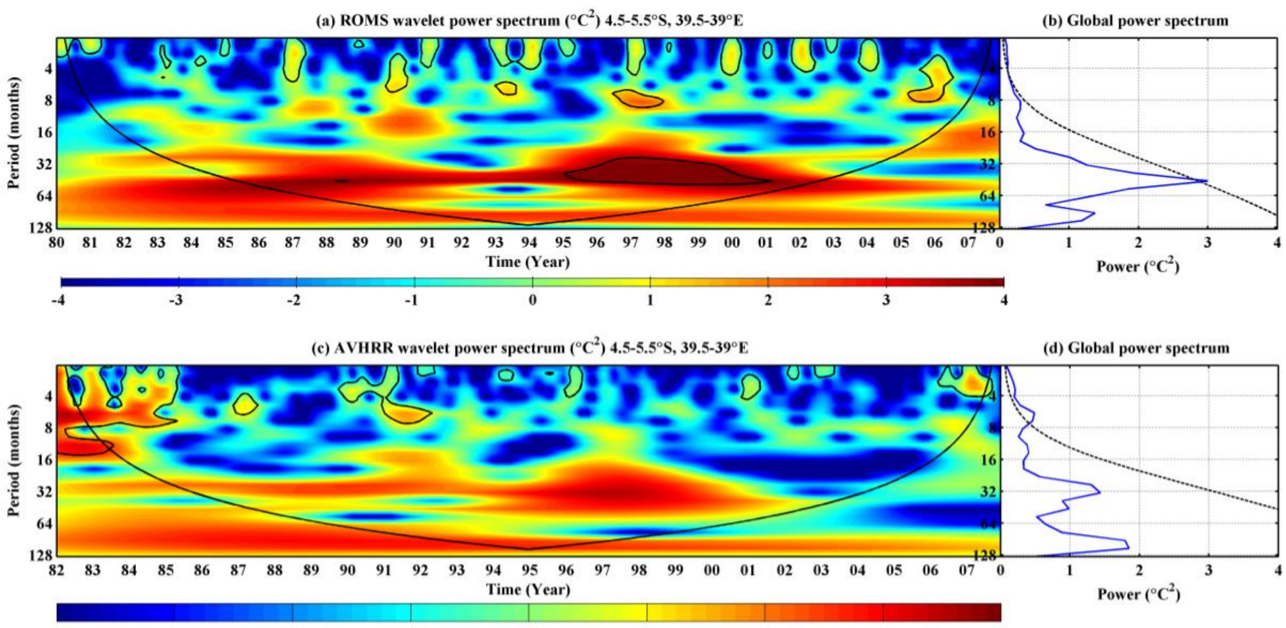


**Figure 5.** Wavelet power spectrum (left column) and power of the wavelet analysis (right column; blue line) of the box-averaged monthly SST anomalies off Tanga coast from the model (a and b) and AVHRR (c and d) in the Northern Tanzanian shelf region. The cone of influence is shown as a thin black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

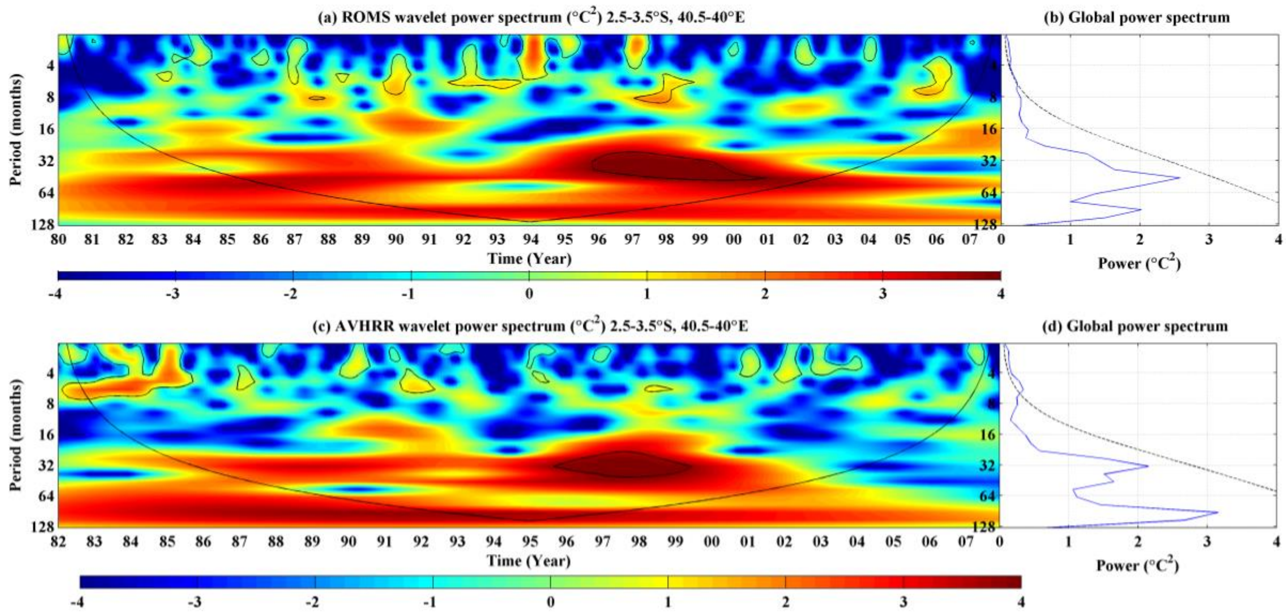


**Figure 6.** Wavelet power spectrum (left column) and power of the wavelet analysis (right column; blue line) of the box-averaged monthly SST anomalies off the Malindi coast from the model (a and b) and AVHRR (c and d) in the Northern Kenya Bank region. The cone of influence is shown as a thin black 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 $^0$C) evident off Malindi than off Tanga (about 1.2 $^0$C) in that year. However, cooler waters (about 2.5$^0$C) were apparent off Malindi compared to about 2.1$^0$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 $^0$C isothermal depth and SSH anomalies

Figure 7 and 8 display Hovmöller plots of SST, the 20 $^0$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 $^o$C isothermal depth was evident comparing to that of SSH anomalies. Deep 20 $^o$C isothermal depth was associated with SSH rise, but the pattern of continuous deep 20 °C isothermal depth from 1994

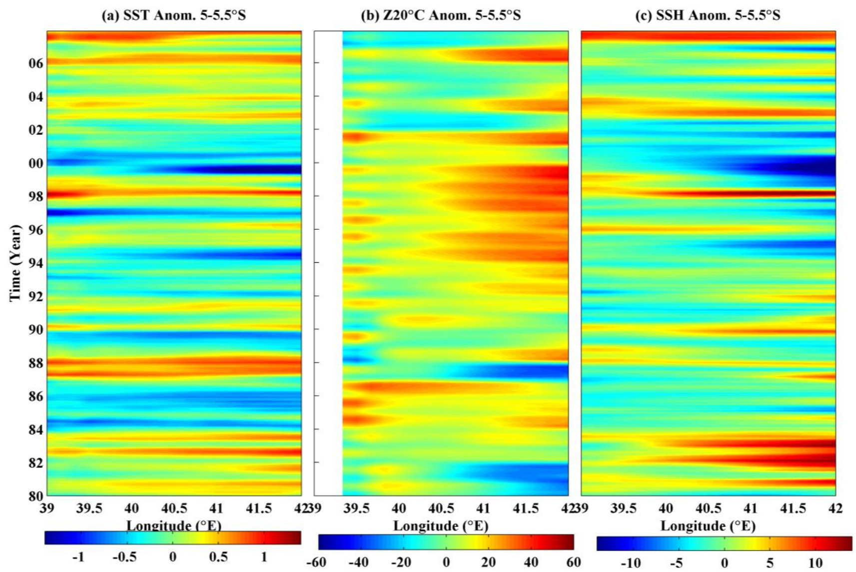


**Figure 7.** Hovmöller plots for ROMS results in the Tanga shelf region from the coast ($39^{o}$E to $42^{o}$E) for monthly anomalies averaged over 5.5–$5^{o}$S of (a) SST in $^{0}$C (b) Z20 $^{0}$C in M and (c) SSH in M from satellite altimetry data.

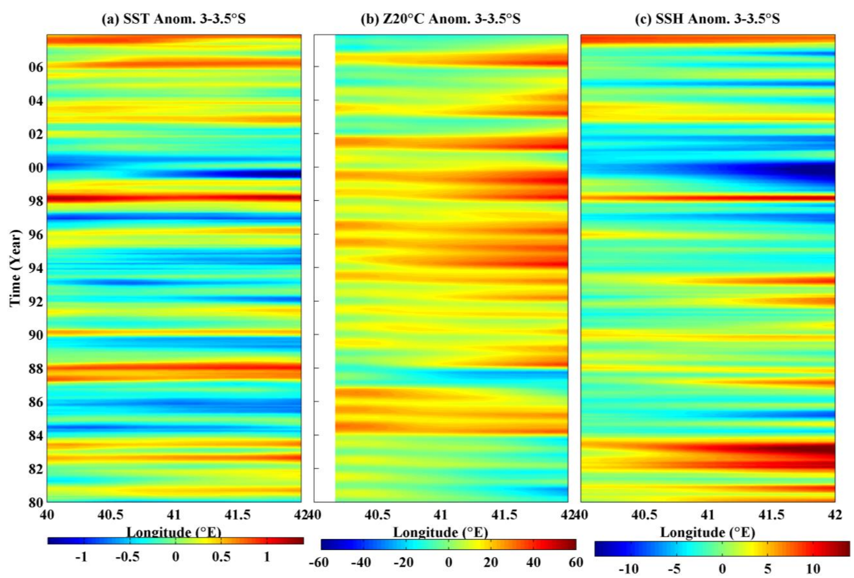


**Figure 8.** Hovmöller plots for ROMS results in the Malindi shelf region from the coast ($40^{o}$E to $42^{o}$E} for monthly anomalies averaged over 3.5–$3^{o}$S of (a) SST in $^{0}$C (b) Z20 $^{0}$C in M and (c) SSH in M from satellite altimetry data.

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.

## References

Collins C, Hermes JC, Reason CJC (2014) Mesoscale activity in the Comoros Basin from satellite altimetry and a high-resolution ocean circulation model. Journal of Geophysical Research 119 (8): 4745-4760

Ducet N, Le Traon PY, Reverdin G (2000) Global high-resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2. Journal of Geophysical Research 105: 19477–19498

Hermes JC, Reason C J (2008) Annual cycle of the South Indian Ocean (Seychelles-Chagos) thermocline ridge in a regional ocean model. Journal of Geophysical Research 113: C04035 [doi: 10.1029/2007JC004363]

Jiddawi NS, Öhman MC (2002) Marine fisheries in Tanzania. Ambio 31: 518-527

Large WG, McWilliams JC, Doney SC (1994) Oceanic vertical mixing: a review and a model with a non-local boundary layer parameterization. Reviews of Geophysics 32: 363-403

Liu Z, Alexander M (2007) Atmospheric bridge, oceanic tunnel, and global climatic teleconnections. Reviews of Geophysics 45: RG2005 [doi: 10.1029/2005RG000172]

Manyilizu M, Dufois F, Penven P, Reason C (2014) Interannual variability of sea surface temperature and circulation in the tropical western Indian Ocean. African Journal of Marine Science 36 (2): 233-252 [doi:10.2989/1814232X.2014.928651]

Manyilizu M (2015) Modelling approach towards a better understanding of sea surface salinity off the East Africa coast. Journal of Informatics and Virtual Education 3 (1): 15-21

Manyilizu M, Penven P, Reason C (2016) Annual cycle of the upper-ocean dynamics in the tropical western Indian Ocean and influences on regional ocean properties. African Journal of Marine Science 38 (1): 81-99 [doi:10.2989/1814232X.2016.1158123]

Marchant R, Mumbi C, Behera S, Yamagata T (2006) The Indian Ocean dipole – the unsung driver of climatic variability in East Africa. African Journal of Ecology 45: 4-16

Mayorga-Adame GC (2007) Ocean circulation of the Zanzibar Channel: A modelling approach. Thesis Research, La Jolla, California, USA [http://www.theissresearch.org/zanzibar/gabriela_final_report.pdf]

Obura D, Celliers L, Machano H, Mangubhai S, Mohammed M, Motta H, Muhando C, Muthiga N, Pereira M, Schleyer M (2002) Status of coral reefs in Eastern Africa: Kenya, Tanzania, Mozambique and South Africa. In: Wilkinson C (ed) Status of coral Reefs of the world, 2002. Global Coral Reef Monitoring Network (GCRMN). Australian Institute of Marine Science, Townsville, Australia. pp 63-78

Penven P, Lutjeharms JRE, Florenchie P (2006) Madagascar: A pacemaker for the Agulhas Current system? Geophysical Research Letters 33: L17609 [doi: 10.1029/2006GL026854]

Reason C, Allan R, Lindesay J, Ansell T (2000) ENSO and climatic signals across the Indian Ocean basin in the global context: Part 1, Interannual Composite Patterns. International Journal of Climatology 20: 1285-1327

Schott FA, Xie SP, McCreary Jr JP (2009) Indian Ocean circulation and climate variability. Reviews of Geophysics 47: RG1002. [doi: 10.1029/2007RG000245]

Shchepetkin A, McWilliams J (2003) A method for computing horizontal pressure-gradient force in an ocean model with a non-aligned vertical coordinate. Journal of Geophysical Research 108: 35.1-35.34

Shchepetkin A, McWilliams J (2005) The Regional Oceanic Modelling system (ROMS): A split-explicit, free-surface, topography following coordinate oceanic model. Ocean Modelling 9: 347-404

Smith WHF, Sandwell DT (1997) Global seafloor topography from satellite altimetry and ship depth soundings. Science 277: 1957-1962

Yamagata T, Behera SK, Rao SA, Guan Z, Ashok K, Saji HN (2003) Comments on 'Dipoles, temperature gradient, and tropical climate anomalies'. Bulletin of the American Meteorological Society 84: 1418–1422

Yamagata T, Behera SK, Luo JJ, Masson S, Jury MR, Rao SA (2004) Coupled ocean–atmosphere variability in the tropical Indian Ocean. In: Wang C, Xie SP, Carton JA (eds) Earth's climate: The ocean-atmosphere interaction. Geophysical Monograph Series 147, AGU, Washington, DC. pp 189-212

# Factors influencing spatial patterns in primary productivity in Kenyan territorial waters

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## Abstract
This study was formulated to investigate productivity systems within Kenyan territorial waters. The interaction of processes on the margins of the marine waters, particularly the influx of fresh water loaded with sediments and nutrients, influences productivity of coastal waters. These deposited sediments, rich in nutrients, create a topographic barrier to the northerly flowing East African Coastal Current (EACC). Phosphate and nitrate peaks observed around the North Kenya Bank area provide evidence of an upwelling event. The contribution of sediments from the Lamu archipelago mangrove system is evident from the high observed particulate organic carbon (POC) input around the area. The system around the Lamu archipelago did not however show high chlorophyll-a levels despite the high POC influx. This may be due to the low levels of limiting phosphate in the surrounding waters, contrary to the observation further north in the region where high chlorophyll-a levels and corresponding higher phosphate levels were apparent. Productivity was largely supported by upwelling and organic matter mineralization. High levels of chlorophyll corresponded to high pelagic fish densities in the south (around 4.5°S) and north of the study area (around 2.5°S).

**Keywords:** Kenya, Pelagic fish densities, Productivity, Nutrients, Silicon, EACC, Upwelling

## Introduction
The Somali Current (SC) and Monsoon winds both influence the distance the EACC travels up the East African coast. During the South-East Monsoon (SEM), the EACC joins the SC north of Malindi and flows northwards to the Horn of Africa. However, during the North-East Monsoon (NEM), the EACC reaches only as far north as Malindi or Lamu, where it meets the opposing Somali Current, the only current off the coast of Kenya that seasonally reverses its flow. The meeting of the two currents results in the formation of the South Equatorial Counter Current (SECC) which is thought to cause upwelling, and may be responsible for the high productivity off the northern Kenyan coast (UNEP, 1998). Upwelling is an oceanographic phenomenon that can bring nutrients and sub-thermocline water rich in dissolved inorganic carbon (DIC) upwards, leading to ecosystem-level biogeochemical responses (Mann and Lazier, 2006).

Upwelling systems have been shown to sustain high numbers of large diatoms (Benitez-Nelson *et al.,* 2007). Similarly, a study conducted by Kenya Marine and Fisheries Research Institute (KMFRI) (2018) off Kiunga, Kiwayu, Lamu and Ungwana Bay observed high plankton densities caused by a diatom bloom of *Chaetoceros* sp. while supported by enhanced nutrients levels diatoms will accumulate biomass with silicate and nitrate at a molar ratio of ~1:1; the limitation being the availability of sufficient light and iron (Brzezinski *et al.,* 2003). The biomass generated in the euphotic zone undergoes gravitational settling where remineralization occurs in deeper waters. Under high pressure in the deeper waters, silicate is mineralized faster and tends to accumulate. Researchers have employed this phenomena where available silicate [$Si(OH)_4$] in the water is enhanced relative to nitrates [$NO_3^-$], and used it as a tracer of the return path of deep upwelled waters.

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The difference between available $Si(OH)_4$ and $NO_3^-$, denoted as Si*, can therefore provide an indication of deep nutrient-rich upwelled waters (Sarmiento *et al.,* 2004). The distribution of nutrients in the ocean is mainly controlled by biogeochemical processes such as the production and decomposition of biogenic organic matter and the sinking of particulate matter (Broecker and Peng, 1982).

## Materials and methods

### Study area

Sampling was conducted during the NEM (24th November to 17th December 2016, and 6th to 21st February 2017). The study sites were chosen to be representative of the territorial waters. The territorial waters included the areas from about 4.5°S (towards the Tanzania boarder) to about 1.5°S (towards the Somali boarder).

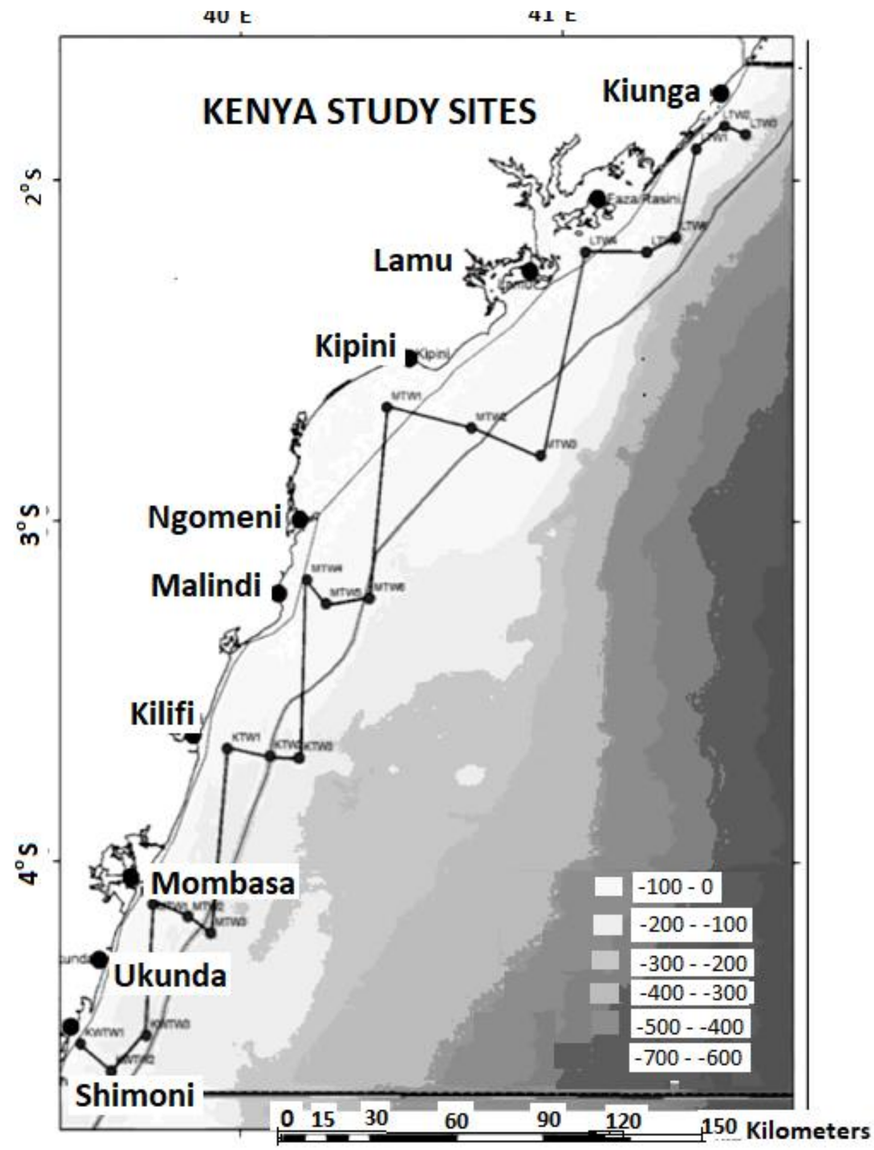


**Figure 1.** Map showing the location of sampling stations off the coast of Kenya.

The objective of this study was to try and answer the following two questions: i) What are the drivers of primary productivity in Kenyan territorial waters; and ii) What is the relationship between levels of primary production and stocks (biomass) of pelagic fish in the area of study?

### Methods

Water samples were collected from a maximum depth of 300 m in the territorial waters at the stations indicated in Figure 1. The vertical profile water sampling was set at intervals of 20 m.

Temperature, dissolved oxygen (DO), pH and salinity were measured *in situ*, while samples collected for nutrients, POC and chlorophyll-a were analysed in the laboratory. The physicochemical parameters were measured using a Sea-Bird CTD (SBE 19 plus V2 SeaCAT CTD) equipped with a SBE 63 optical dissolved oxygen sensor, and a SBE 27 pH/ORP was used to measure pH. Temperature was measured in ITS-90 degrees Celsius (°C), while the salinity was calculated from the conductivity sensor. pH probes were calibrated using 4 and 10 pH buffers while quality control on dissolved oxygen measurements was checked by determining a representative sample for DO using the Winkler method (Parsons *et al*., 1984). Samples for Chlorophyll-a analysis were collected in pre-rinsed plastic bottles, and were filtered under vacuum onto 25mm Whatman GF/F glass fibre filter papers. The filter papers were frozen at -20 °C in aluminium foil pouches for analysis ashore. Chlorophyll-a was measured spectrometrically (on a Thermo Fisher Scientific Model Genesys 10S, USA make) after extraction in 90 % acetone. Nutrient samples were frozen at -20°C awaiting analyses in the laboratory using a four-channel auto-analyzer (Seal QUAATRO Auto Analyzer). POC samples were analyzed using the dichromate redox colorimetric method. The dichromate redox colorimetric method utilizes the formation of the green Cr III species resulting from the reduction of the orange dichromate Cr VI species. The amount of dichromate consumed is determined against a set of standards and measured on a spectrometer in the visual range (600 nm). The analyzed data is presented in Ocean Data View (ODV) software as spatial surface plots and spatial vertical profile plots.

Acoustic measurements using a 38 kHz Simrad EK60 echosounder indicated the pelagic fish densities in the study area. The data generated was processed with Echoview 8™ software. Transects were stratified by day and night and further split into single targets and integrations. The integrated dataset was analyzed using a literature-defined target strength value of -34 dB/kg as a representation of the dominant fish species within the study area, constituted mainly of Carangidae. The target strength employed was adopted from a hydroacoustic survey conducted in the Eastern Indian Ocean by RV *Dr Fridtjof Nansen* (Aglen, 1983). The data was further split into 3 layers with pelagics falling within the 100 m depth zone, followed by mesopelagics within the 100 to 350 m depth zone. The data was then further interpolated using the nearest neighbour algorithm.

Figures 2 to 5 were generated using the open-source ODV software. The software has also been employed to project surface scatter plots of multiple variables to investigate possible relationships.

Satellite data was obtained from the High-Resolution Chlorophyll, US-NASA Aqua MODIS 0.05-degree resolution satellite mission. The satellite-borne sensor was designed to collect global ocean biological data. Its primary mission was to quantify chlorophyll produced by marine phytoplankton. The NetCDF 0.05-degree monthly climatological data of December 2016 (available at https://modis.gsfc.nasa.gov/data/) was downloaded and resampled to the Area of Interest. The ASCII values were converted to Chlorophyll values in mg m-3 and classified using QGIS software.

## Results and discussion

### Carbon transformation

The southern (towards the border with Tanzania) and northern (towards the border with Somalia) territorial water regions exhibited lower surface pH values (ranging between 8.04 and 8.08) compared to the other regions within the territorial waters (Fig. 2). The pH levels were however consistent with the pH values found in most surface ocean waters; i.e. ~8.1 (Capone and Hutchins, 2013). The southern region (bordering Tanzania) did however post lower than average pH levels (8.04). This can be attributed to higher levels of dissolved $CO_2$, either due to the mineralization of the organic carbon generated by the adjacent mangrove ecosystem or the effect of global warming through ocean acidification. $CO_2$ produced through photosynthesis is the main raw material used in the building up of organic matter, thus with the advent of organic matter remineralisation, it will constitute a part of the generated degradation products contributing to a lowering of the seawater pH. At seawater pH, >99% of $CO_2$ species exist in the form $HCO^{3-}$ and $CO_3^{-2}$. Deeper waters carry high levels of $CO_2$, which are brought to the surface as dense cooler nutrient-rich waters during upwelling, representing the biogeochemical imprint of accumulated microbial respiration of organic matter (Capone and Hutchins, 2013). Hauri *et al.* (2013), using model simulations, further observed large gradients in $CO_2$ concentrations between freshly upwelled water and older upwelled water, which can be attributed to the carbon species Model simulations conducted on the central California upwelling system showed that pH can range between 7.85 and 8.15 as a result of this variability (Hauri *et al.,* 2013). The Mombasa region posted higher pH levels at 8.75 which could be linked to anthropogenic inputs into the ocean. Kamau *et al.* (2015) reported sewage discharges close to the mouth of Tudor Creek located in Mombasa. Phytoplankton have also been observed to deplete seawater $CO_2$ concentrations in highly productive regions (Capone and Hutchins, 2013), which supports the idea that the high productivity around Ungwana Bay may be associated with the relatively high pH in the area (Fig. 2 and 4).

## Productivity

The high Chlorophyll-a concentrations found in the southern sector can be attributed to riverine input of terrestrial origin (Fig. 4). The salinity ranged between 32 ‰ to 33 ‰, and the adjacent coastline also has patches of mangrove forest that further contribute to organic matter influx. Rainfall and subsequent freshwater influx into coastal waters have been reported to be important contributors towards local productivity due to terrigenous nutrient loading (Lugomela *et al.*, 2001; Heip *et al.*, 1995). The area however posted low nutrients level in its surface waters. This this could be associated with enhanced uptake due to the high productivity observed in the area (Fig. 4). Omand and Mahadevan (2015) similarly reported low surface nutrient levels in areas associated with high productivity. The southern region presents an area of low surface temperature, and this may be associated with an upwelling phenomenon (Fig. 4). Studies elsewhere have associated low temperatures to the upward movement of cool deep waters propelled by upwelling (Grasse *et al.*, 2016; El Sayed *et al.*, 1994). The Tyro expedition conducted along the Kenyan coast caught a slender guitarfish (*Rhinobatos holcorhynchus*) in shallow waters at the mouth of Gazi Bay and attributed its presence to upwelling (Heip *et al.*, 1995). This rare fish species is normally caught at depths of 75 - 183 m in cooler deep waters (Compagno *et al.*, 1989, Smith and Heemstra, 1986).

Figure 3 makes a comparison between chlorophyll satellite imagery and the actual on-site measurements conducted from the RV *Mtafiti*. The chlorophyll-a spatial distribution plot (Fig. 3, plot 2) correlated well with the December 2016 monthly averaged satellite ocean coluor data (Fig. 3, plot 1). The satellite image integrates both surface and the limits of light penetration and projects monthly averages. This may explain the difference between surface chlorophyll-a data and the satellite image in the region labeled 'A'. While the same area was presented by satellite images as being highly productive, this was not clearly shown in the surface plots. However, a high chlorophyll-a signal was recorded on a vertical chlorophyll-a profile at around 10 to 80 m depths. The satellite signal is however relatively higher than *in situ* measurements and the midwater maxima might not provide an exhaustive explanation to the high signal in region A. Whereas the

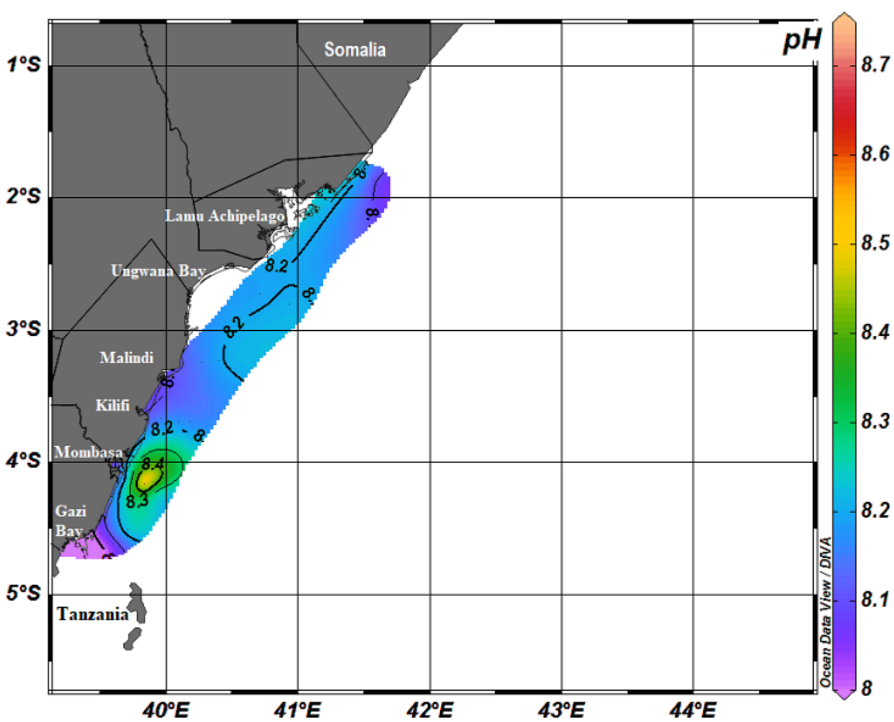


**Figure 2.** Spatial surface pH distribution within the territorial waters of Kenya.

satellite image signal is a monthly average, the *in situ* measurement is a once-off measurement and might easily have missed out one or more phenomena. The area A with a high chlorophyll-a signal is located within the North Kenya Bank region where, during the NEM (incidentally the period during which sampling was conducted in the present study) the northerly flowing EACC meets with the reversed SC and forms a counter current that flows in a south easterly direction. This results in deep nutrient rich waters flowing in to balance the water mass outflow due to the counter current (Jacobs *et al.,* 2020). The high chlorophyll-a signature in area A can thus be attributed to upwelling. The area also experiences localized perturbation due to topographic forcing as the EACC collides with the North Kenya Bank (Johnson *et al.,* 1982). The effect of the localized mixing might only be felt at sections just above the bank, causing the enhancement of nutrients in the surrounding waters and contributing to the observed below-water chlorophyll maxima reflected in Figure 3, plot 3.

## Biogeochemical processes

Figure 4 shows a plume of Si, Si* and POC in the areas around Ungwana bay, the North Kenya Bank and Lamu archipelago. This could be attributed to the influx of riverine Si rich waters from the Tana River discharging into Ungwana Bay. Other sources could be associated with runoff from the Si-rich mangroves of Lamu archipelago during ebbing of the tide, and the contribution due to upwelling that has been reported to occur seasonally in the months of December to February during the NEM on the North Kenya Bank (Jacobs *et al.,* 2020). The elevated $Si(OH)_4$ concentrations are either a consequence of dissolution of biogenic silica ($bSiO_2$) shells in the water column, or of release from the sediments (Natori *et al.,* 2006; Lewin, 1961). The contribution of the Lamu archipelago mangrove system to organic matter flux is evident from the high observed POC input around this area. Djurhuus *et al.* (2017) reported a positive correlation between POC and particle concentration (cp), here represented by the corresponding high Si level.

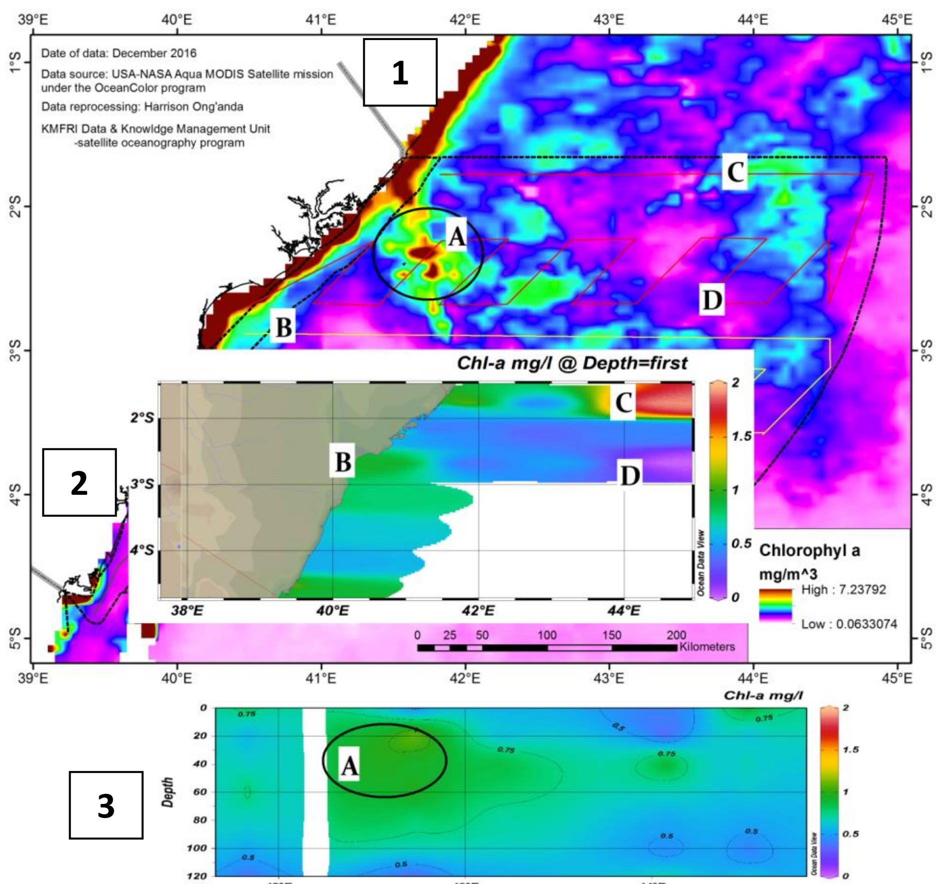


**Figure 3.** Spatial surface chlorophyll-a distribution as determined during the December 2016 RV *Mtafiti* cruise and as presented by ocean colour Aqua MODIS satellite data. The plot labeled 1 represents the satellite image; plot labeled 2 represents surface spatial chlorophyll-a distribution; plot labeled 3 represents chlorophyll-a vertical spatial distribution along the latitudes 2°S to 3°S and longitudes 42°N to 44°N.

The correlation between the number of particles and microbial abundance has been well demonstrated, denoting that POC concentrations and microbial abundance are positively correlated to particle concentration (Azam and Malfatti, 2007; Ghiglione *et al.*, 2007). Thus, more POC creates an elevated food resource for bacterial organisms attaching to the particles, resulting in a greater abundance of microorganisms and a higher mineralization rate (Azam and Malfatti, 2007; Ghiglione *et al.*, 2007). This therefore implies that the productivity of the surrounding system is enhanced by the mineralization of the POC supplied by the mangrove system of the Lamu archipelago. The elevated phytoplankton growth is boosted by the high temperature and the availability of light and nutrients (Behrenfeld *et al.*, 2006). The system around the Lamu archipelago did not however post high chlorophyll-a levels despite the high POC influx. This may be due to the low phosphate levels (limiting production) in the surrounding waters as observed in Figure 4. The region further north posted high chlorophyll-a levels and corresponding higher phosphate levels. There is the possibility of a time lag in mineralisation occurring further north as the water mass flows along the northward EACC current.

The biogeochemical functioning of the North Kenya bank is complex, and it is largely driven by the interplay of Tana River run-off, hydrodynamics, and air-sea interactions. Dominant winds act as important forcing components in a system resulting in either upwelling or downwelling (Fraysse *et al.*, 2014; Pairaud *et al.*, 2011; Millot, 1990). It is presumed that the productivity of the North Kenya Bank is driven by the upwelling of the monsoon systems. Ocean currents are important features that influence nutrient availability and determine productivity. The area under study is where the south flowing SC meets the north flowing EACC during the NEM season (November to March) causing upwelling and nutrients enrichment (Jacobs *et al.*, 2020; Johnson *et al.*, 1982).

As shown in Figure 4, the area around the North Kenya Bank experienced elevated nitrate and phosphate

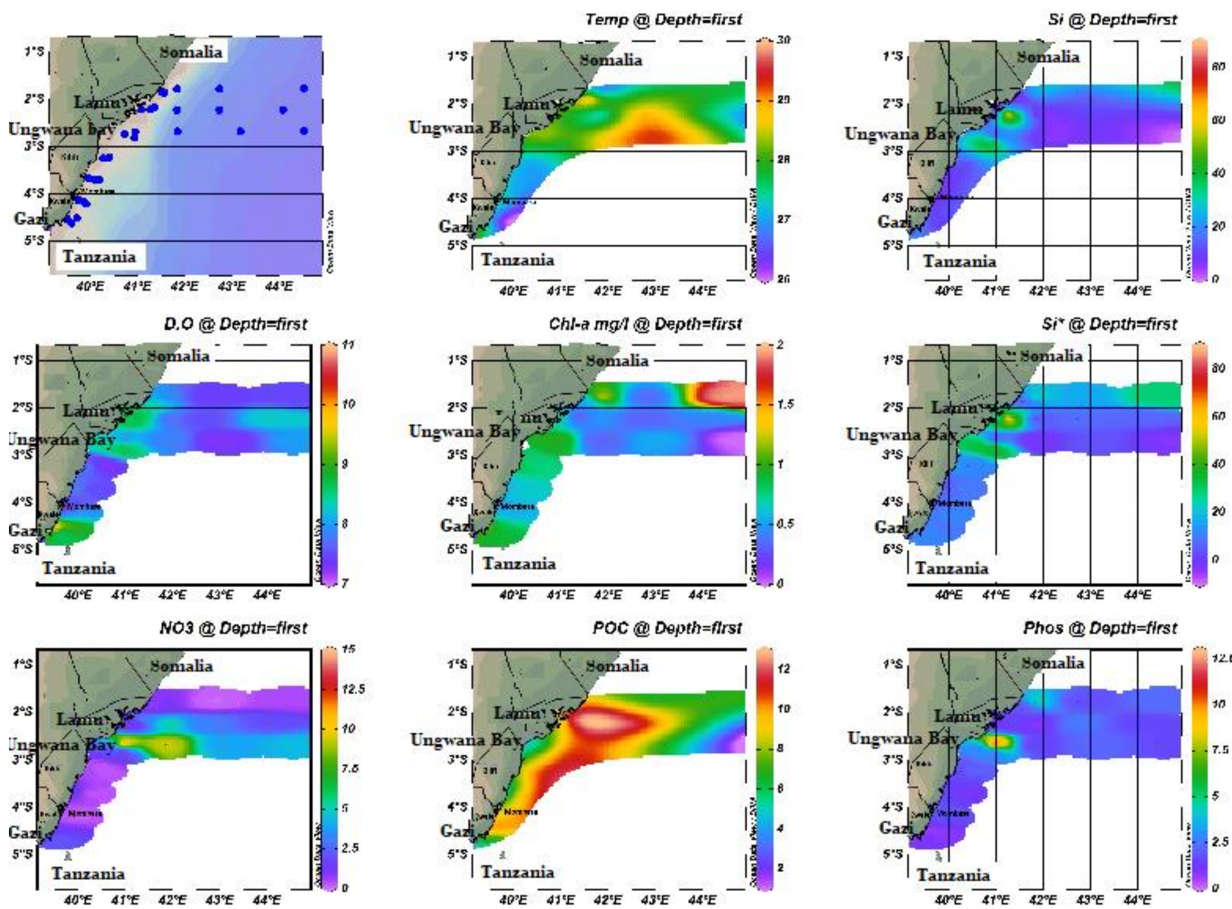


**Figure 4.** Spatial surface distribution of DO, POC, $NO_3^-$, Phosphate, Chl-a, Si*,Si and temperature, as determined during the December 2016 RV *Mtafiti* cruise.

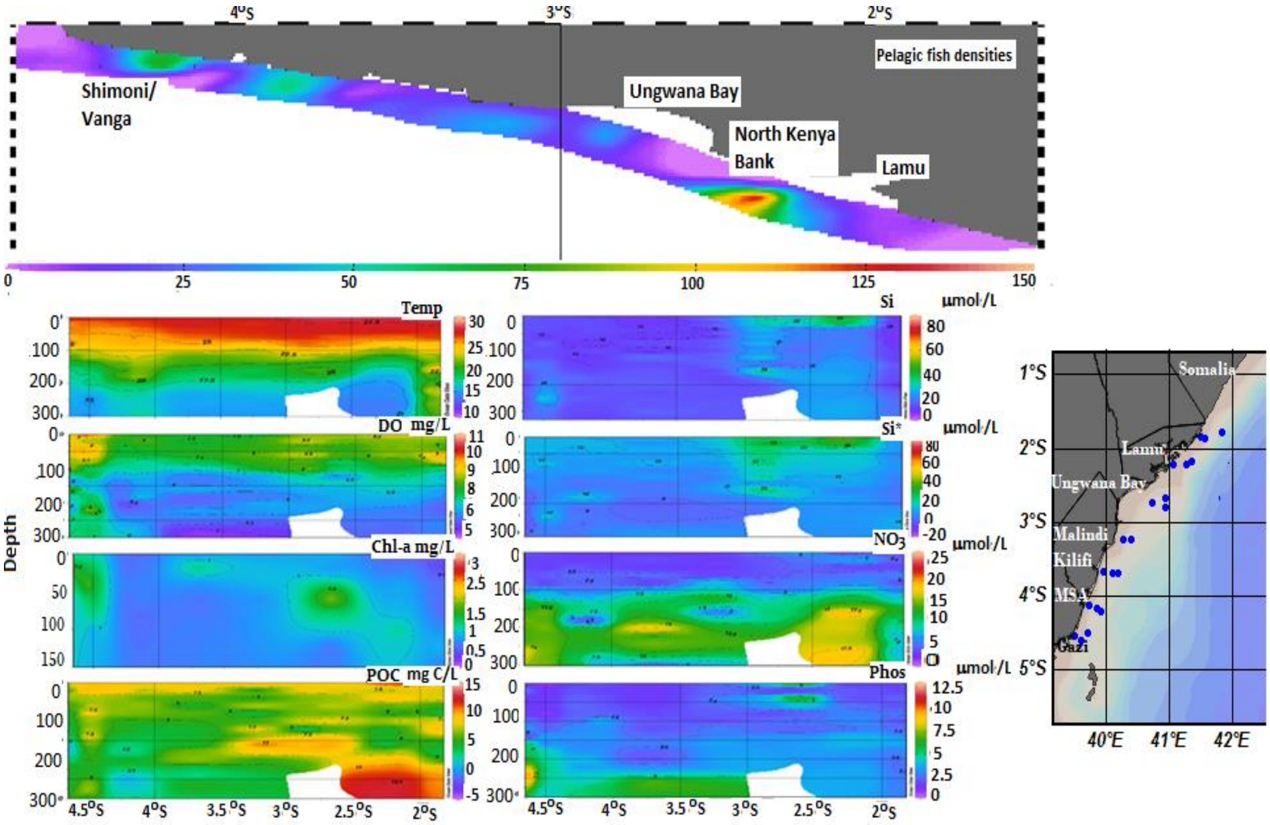


**Figure 5.** Vertical profiles showing physicochemical parameters, nutrient distribution and pelagic fish densities. The labeled map provides site information with latitude and longitude coordinates which provide insight on the actual location of the vertical profile plots.

levels, suggesting that a phenomenon is at play that results in a high spike of these nutrients. It has been reported that the major oceanic source of phosphorus is riverine inputs (Paytan and McLaughlin, 2007). Kitheka *et al.* (2005) reported the annual total sediment load discharged by the Tana River to be $6.8\times10^{6}$ tons $yr^{-1}$. These deposited sediments, rich in nutrients, create a pool of nutrients that is resuspended as the system is perturbated by the northerly flowing EACC, while the interaction of the EACC with the North Kenya Bank diverts the water mass upwards resulting in the upward flow of nutrient rich waters (Jacobs *et al.,* 2020). Johnson *et al.* (1982) postulated that the deflection of the EACC seaward at its point of convergence with the SC is mainly due to topographic forcing by the North Kenya Bank.

The northern region around Lamu and Kiwayu showed high surface POC levels, probably due to the surrounding mangroves in the region (Fig. 5). Whereas there seems to be some vertical mixing in relation to POC at the area around 2.5°S to 3°S representing the North Kenya Bank, there seems to be some stratification in relation to POC between 2.5°S to 2°S. The high POC level at around 300 m is probably due to re-suspension of organic matter at the bank edges. High productive regions have been reported to often have relatively large size primary producers that sink faster through the water column, yielding a relatively export efficient water column (Henson *et al.,* 2012). Figure 5 tends to corroborate these findings where there seems to be a homogeneous POC distribution in the water column in the areas associated with high productivity around the North Kenya Bank (2.5°S to 3°S) and the southern end of the study area (4°S). According to Henson *et al.* (2012) organisms in such productive areas are prone to degradation and rapid remineralization after leaving the euphotic zone. Figure 5 shows a high $NO_3$ and $PO_4$ signal corresponding to the area below the euphotic zone and within the same area associated with high POC levels. The high $NO_3$ and $PO_4$ can be attributed to the mineralization of the sinking POC (Henson *et al.,* 2012).

The area around the North Kenya Banks and Lamu showed elevated Si* levels on the surface. Whereas the area around Lamu (~2°S) only posted high Si* levels on the surface, that at the Bank (2.5°S to 3°S) indicated a vertical Si* flux. This is illustrated better by the Si vertical distribution; it shows an upward flow of Si from deeper waters deflected upwards by the Bank (Fig. 5). The high Si* signature at the North Kenya Bank can therefore be attributed to upwelling as well as terrigenous material, mainly at the surface. While that around the Lamu area can be associated with the influx of organic matter from the rich mangrove forest in the this area.

### Productivity in relation to the fishery

High levels of chlorophyll corresponded to high pelagic fish densities (Fig. 5) in the area to the south around 4.5°S, and north around 2.5°S. The driver of the high pelagic fishery in the north can be attributed to the upwelling around the North Kenya Bank region, while the productivity in the south needs more research to establish the main drivers. A FAO (2016) report, however, suggests that a limited short-lived upwelling feature occurs in southern Kenya and northern Tanzania (Tanga region). Figure 5 shows elevated temperature distribution along the euphotic zone in the North Kenya Bank area around 2.5°S to 3°S, corresponding to a chlorophyll subsurface maximum around the same area. Nakamoto *et al*., (2000) used phytoplankton pigment concentrations derived from the coastal zone colour scanner (CZCS) to force an isopycnal ocean circulation model coupled to a mixed-layer model and showed that higher chlorophyll concentrations increased the amount of solar energy absorption and the rate of heating in the upper ocean. It has however, been reported that changes in SST are likely to result in a fundamental re-distribution of small pelagic fish species (Groeneveld, 2014). Fishbase has collated information and projected a possible re-distribution of species in the year 2100 (Groeneveld, 2014). A number of small pelagic species are expected to extend their ranges southward from the Arabian Gulf region and the coast of Somalia, to Kenya, Tanzania and perhaps as far south as Mozambique and Madagascar. Interestingly, two of these species (*Sardinella gibbosa* and *Dussumieria acuta*) are already identified as key components of the catch in Tanzania (Groeneveld, 2014).

## Conclusion

The productivity of Kenyan territorial waters is driven by the influx of nutrients and terrigenous material from the river systems (mainly Tana River) and the mangrove ecosystems. The regions associated with high productivity, deduced through the proxy chlorophyll-a, were also associated with high fish densities. The fish density signal was highest on the North Kenya Bank and in the south around the Vanga-Shimoni area. Upwelling and associated terrigenous mineralization account for much of the productivity at the sites associated with high productivity. The area, being located at the tropics, is associated with high temperature and light intensity thus enhancing nutrient uptake in the euphotic zone. The high nutrient uptake in the euphotic zone attributes to the observed stratification of the vertical nutrient distribution. The North Kenya Bank experiences localized perturbation due to topographic forcing as the EACC collides with the bank generating an ecosystem with high productivity.

## Acknowledgements

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## References

Aglen A (1983) R/V *Dr Fridtjof Nansen*: Determination of calibration constants. In: FAO/GFCM, 1983. pp 19-22. Report of the technical consultation on acoustic methods for fish detection and abundance estimation, held at Palma de Mallorca, Spain, 8-12 November 1982. FAO Fisheries Report (277): 94 pp

Azam F, Malfatti F (2007) Microbial structuring of marine ecosystems. Nature Reviews Microbiology 5 (10): 782

Behrenfeld MJ, O'Malley RT, Siegel DA, McClain CR, Sarmiento JL, Feldman GC, Milligan AJ, Falkowski PG, Letelier RM, Boss ES (2006) Climate-driven trends in contemporary ocean productivity. Nature 444 (7120): 752 [doi:10.1038/nature05317]

Benitez-Nelson CR, Bidigare RR, Dickey TD, Landry MR, Leonard CL, Brown SL, Nencioli F, Rii YM, Maiti K, Becker JW, Bibby TS, Black W, Cai WJ, Carlson CA, Chen F, Kuwahara VS, Mahaffey C, McAndrew PM, Quay PD, Rappe MS, Selph KE, Simmons MP, Yang EJ (2007) Mesoscale eddies drive increased silica export in the subtropical Pacific Ocean, Science 316: 1017–1021 [doi:10.1126/science.1136221]

Broecker WS, Peng TH (1982) Tracers in the sea. Eldigio Press, Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York. 690 pp

Brzezinski MA, Dickson ML, Nelson DM, Sambrotto R (2003) Ratios of Si, C and N uptake by microplankton in the Southern Ocean. Deep Sea Research Part II: Topical Studies in Oceanography 50 (3-4): 619-633

Capone DG, Hutchins DA (2013) Microbial biogeochemistry of coastal upwelling regimes in a changing ocean. Nature Geoscience 6 [doi: 10.1038/NGEO1916]

Compagno LJ, Smale MJ, Davis B, Cliff G, Dudley SF (1989) Sharks and the Natal sharks board. Oceans of Life off Southern Africa. pp 198-213

Djurhuus A, Read JF, Rogers AD (2017) The spatial distribution of particulate organic carbon and microorganisms on seamounts of the South West Indian Ridge. Deep Sea Research Part II: Topical Studies in Oceanography 136: 73-84

El Sayed MA, Aminot A, Kerouel R (1994) Nutrients and trace metals in the northwestern Mediterranean under coastal upwelling conditions. Continental Shelf Research 14 (5): 507-30

Food and Agriculture Organization (FAO) (2016) Case studies on climate change and African coastal fisheries: a vulnerability analysis and recommendations for adaptation options Circular No 1113: ISSN 2070-6065

Fraysse M, Pairaud I, Ross ON, Faure VM, Pinazo C (2014) Intrusion of Rhone River diluted water into the Bay of Marseille: Generation processes and impacts on ecosystem functioning. Journal of Geophysical Research: Oceans 119 (10): 6535-6556

Ghiglione JF, Mevel G, Pujo-Pay M, Mousseau L, Lebaron P, Goutx M (2007) Diel and seasonal variations in abundance, activity, and community structure of particle-attached and free-living bacteria in NW Mediterranean Sea. Microbial Ecology 54 (2): 217-31

Grasse P, Ryabenko E, Ehlert C, Altabet MA, Frank M (2016) Silicon and nitrogen cycling in the upwelling area off Peru: A dual isotope approach. Limnology Oceanography 61: 1661-1676

Groeneveld JC, Cliff G, Dudley SF, Foulis AJ, Santos J, Wintner SP (2014) Population structure and biology of shortfin mako, *Isurus oxyrinchus*, in the south-west Indian Ocean. Marine and Freshwater Research 65 (12): 1045-58

Hauri C, Gruber N, Vogt M, Doney SC, Feely RA, Lachkar Z, Leinweber A, McDonell AMP, Munnich M, Plattner GK-K (2013) Spatiotemporal variability and long-term trends of ocean acidification in the California Current System. Biogeosciences 10: 193-216

Heip CHR, Hemminga MA, De Bie MJM (1995) Monsoons and coastal ecosystems in Kenya. Cruise reports: Netherlands Indian Ocean Programme. National Museum of Natural History, Leiden: ISBN 90-73239-29-X ; VOLO~5

Henson S, Lampitt R, Johns D (2012) Variability in phytoplankton community structure in response to the North Atlantic Oscillation and implications for organic carbon flux. Limnology and Oceanography 57 (6): 1591-601

Jacobs ZL, Jebri F, Raitsos DE, Popova E, Srokosz M, Painter SC, Nencioli F, Roberts M, Kamau J, Palmer M, Wihsgott J (2020) Shelf-break upwelling and productivity over the North Kenya Banks: The importance of large-scale ocean dynamics. Journal of Geophysical Research: Oceans 125: e2019JC015519

Johnson DR, Mutua M, Kimani EJ (1982) Response to annually reversing monsoon winds at the southern boundary of the Somali Current. Deep Sea Research 29: 1217-1227

Kamau JN, Machiwa PK, Adriano MJ, Sibylle M, Mwangi S, Munga D, Kappelmeyer U (2015) Investigating the distribution and fate of Cd, Cu, Fe, Mn and Zn in sewage impacted mangrove fringed creeks of Kenya, Tanzania and Mozambique. Journal of Soils and Sediments 15: 2453-2465

Kitheka JU, Obiero M, Nthenge P (2005) River discharge, sediment transport and exchange in the Tana Estuary, Kenya. Estuarine Coastal and Shelf Science 63 (3): 455-468

KMFRI (2018) The RV *Mtafiti*: Marine research towards food security and economic development for Kenya. Njiru JM, Ruwa RK, Kimani EN, Ong'anda HO, Okemwa GM, Osore MK (eds). Kenya Marine and Fisheries Research Institute, Mombasa, Kenya. 102 pp

Lewin JC (1961) The dissolution of silica from diatom walls. Geochimica et Cosmochimica Acta 21 (3-4): 182-98

Lugomela C, Wallberg P, Nielsen TG (2001) Plankton composition and cycling of carbon during the rainy season in a tropical coastal ecosystem, Zanzibar, Tanzania. Journal of Plankton Research 23 (10): 1121-36

Mann KH, Lazier JRN (2006) Biological-physical interactions in the ocean. In: Dynamics of marine ecosystems. Blackwell Science, Cambridge, Massachusetts. 496 pp. ISBN: 1-4051-1118-6. 2006 [doi:10.1002/9781118687901]

Millot C (1990) The gulf of Lions' hydrodynamics. Continental Shelf Research 10 (9-11): 885-894

Nakamoto S, Prasanna KS, Oberhuber JM, Muneyama K, Frouin, R (2000) Chlorophyll modulation of sea surface temperature in the Arabian Sea in a mixed layer-isopycnal general circulation model. Geophysical Research Letters 27: 747–756

Natori Y, Haneda A, Suzuki Y (2006) Vertical and seasonal differences in biogenic silica dissolution in natural seawater in Suruga Bay, Japan: Effects of temperature and organic matter. Marine Chemistry 102 (3-4): 230-241

Omand MM, Mahadevan A (2015) The shape of the oceanic nitracline. Biogeosciences 12 (11): 3273-3287

Pairaud IL, Gatti J, Bensoussan N, Verney R, Garreau P (2011) Hydrology and circulation in a coastal area off Marseille: Validation of a nested 3D model with observations. Journal of Marine Systems 88 (1): 20-33

Parsons TR, Maita Y, Lalli CM (1984) A manual of chemical and biological methods for seawater analysis. Pergamon Press, Oxford, UK. 173 pp

Paytan A, McLaughlin K (2007) The oceanic phosphorus cycle. Chemical reviews 107 (2): 563-76

Sarmiento JL, Gruber N, Brzezinski MA, Dunne JP (2004) High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427: 56-60

Smith MM, Heemstra PC (1986) Smiths' Sea Fishes. Macmillan. Johannesburg, South Africa. 1047 pp

United Nations Environmental Programme (UNEP)(1998) Eastern Africa atlas of coastal resources. UNEP Regional Reports and Studies No. 1. Nairobi, Kenya. 114 pp

# Coastal upwelling and seasonal variation in phytoplankton biomass in the Pemba Channel

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## Abstract
This study was conducted in the Pemba Channel off Tanga Region in northern Tanzania to investigate physical and chemical factors that drive changes in phytoplankton biomass. Three transects off Mwaboza, Vyeru and Sahare were selected. For each transect, ten stations were sampled. Phytoplankton biomass was determined as chlorophyll-*a* (Chl-*a*) concentration. Similarly, physico-chemical variables (temperature, salinity, dissolved oxygen, pH and nutrients) were determined. It was observed that the Chl-*a* concentration was significantly higher during the northeast monsoon (median 1.44 mg $m^{-3}$) as compared to the southeast monsoon (median 1.19 mg $m^{-3}$; W = 2216, p = 0.029). The higher productivity during the northeast monsoon is attributed to the presence of high-nutrient water caused by coastal upwelling. It is concluded that indication of upwelling, observed through relatively low temperatures during the northeast monsoon season, could be responsible for bringing nutrient-rich waters to the surface, which in turn stimulated the increase in Chl-*a* concentration.

**Keywords:** Chlorophyll-*a*, SST, Pemba Channel, Upwelling, Monsoon seasons

## Introduction
Phytoplankton are important in the ocean food webs as primary producers which transfer energy from the sun to higher trophic levels through photosynthesis (Vargas, 2006) and contribute about half of the earth's oceanic and terrestrial primary production (Barlow *et al.*, 2008; Field *et al.*, 1998; Gröniger *et al.*, 2000). In the marine environment, phytoplankton contribute more than 90 % of the total marine primary production (Duarte and Cebrián, 1996). However, the relationship between primary production and Chl-*a* concentration is not always linear (Kyewalyanga, 2002). Due to the difficulty in computing primary production, scientists often use Chl-*a* concentration as a proxy for primary productivity (Ezekiel, 2014; Limbu and Kyewalyanga, 2015; Moto and Kyewalyanga, 2017; Peter, 2013; Semba *et al.*, 2016). However, Barlow *et al.* (2011) estimated primary productivity in the coastal waters of Unguja and Pemba Islands directly from photosynthesis–irradiance combined with measured Chl-*a*.

Phytoplankton distribution and production vary both in space and time, caused by variation in chemical and physical factors. Some of these factors include carbon dioxide, sunlight, nutrients, temperature, water depth, bottom topography, upwelling, presence of grazers, salinity, dissolved oxygen and water pH (Bouman *et al.*, 2003; Gallienne and Smythe-Wright, 2005; Lamont and Barlow, 2015; Lee *et al.*, 2012; Meyer *et al.*, 2002; Sá *et al.*, 2013). In Tanzanian coastal waters, several studies reported on spatial and temporal variation in Chl-*a* and phytoplankton species composition (Kyewalyanga, 2002, 2015; Barlow *et al.*, 2011; Peter, 2013; Ezekiel, 2014; Limbu and Kyewalyanga, 2015; Semba *et al.*, 2016; Moto and Kyewalyanga, 2017). However, information

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on factors that drive the seasonal and temporal variation in phytoplankton is limited. Some studies in the Western Indian Ocean region have related the physical and chemical variables to abundance of phytoplankton (Peter, 2013; Semba *et al.*, 2016). The study by Peter *et al.* (2018) used multivariate analysis to determine the influence of environmental variables on abundance of phytoplankton in the coastal waters of Unguja Island during the northeast and southeast monsoon seasons.

pelagic fishery in the Channel (Bakun *et al.*, 1998). Therefore, to better understand factors that drive the seasonal phytoplankton biomass in the nearshore waters of the Pemba Channel, the present study attempts to answer the following questions: Is there any evidence of upwelling in the nearshore areas of the Pemba Channel?; To what extent does upwelling affect phytoplankton biomass in the area?; and, What other physical and chemical factors influence seasonal variation in phytoplankton biomass?

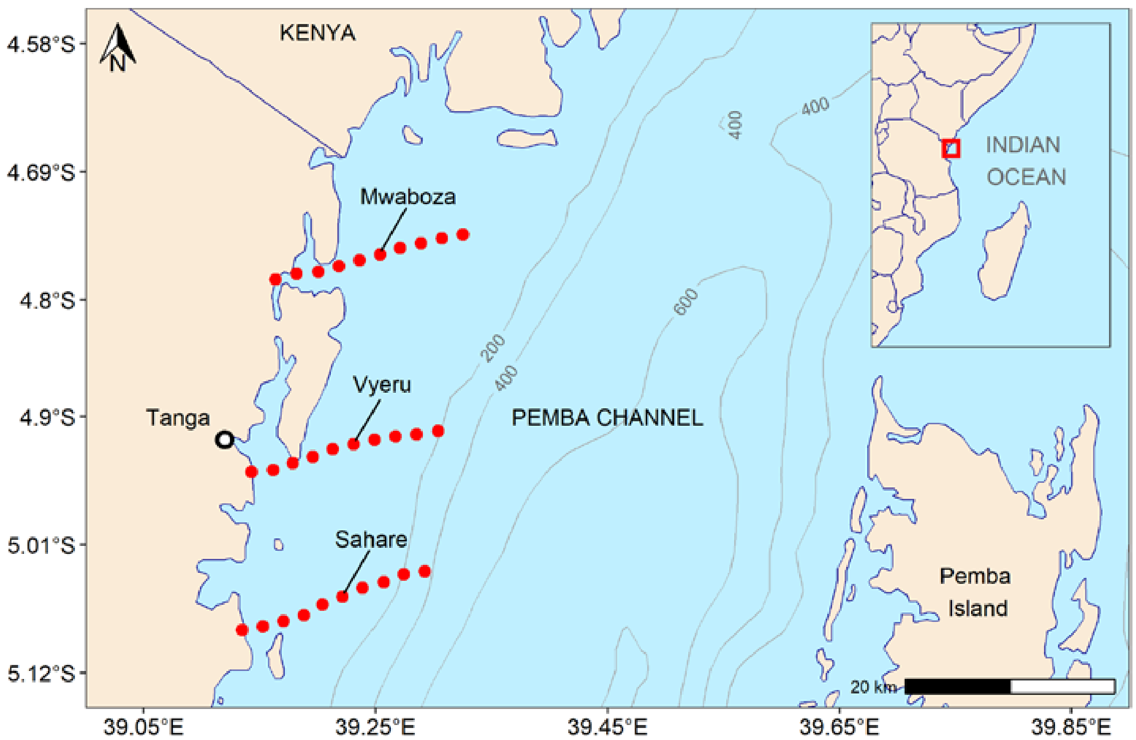


**Figure 1.** A map of the western Pemba Channel showing the study area. The inset map locates the study area in the Indian Ocean. Grey lines are isobars of 200 m interval contours. Red circles represent sampling stations along each transect.

These previous studies mainly focused on the association between Chl-*a* and environmental variables, and found weak relationships between them. Ultimately, the results are inconclusive in identifying the combined effect of more than one variable acting at the same time to influence the growth and production of phytoplankton at any given location in a particular season. In this study, it is hypothesized that the western side of the Pemba Channel is influenced by the prevailing winds, effecting a subsidiary branch of the East African Coastal Current (EACC) and leading to coastal upwelling during the northeast monsoon. These upwelling events promote growth of phytoplankton leading to higher production of the small

To address these questions, *in-situ* observation and satellite data were combined to determine and map potential areas for coastal upwelling on the western side of the Pemba Channel. A non-linear approach was then used to determine physical and chemical variables that contribute to seasonal variation in Chl-*a* concentration. It was anticipated that the study could provide further information to the scientific community and policy makers on the ecological importance of the study area to the pelagic fishery. Further, the *in-situ* measurements gathered in this study may be used to validate satellite data and models, which are important in understanding historical trends and predicting future ocean conditions.

## Materials and Methods

### Study area

This study was conducted in the coastal waters of Tanzania within the Pemba Channel. The study area lies between longitude 39.10°E and 39.70°E and latitude 4.70°S and 5.10°S (Fig. 1). Three transects located off three landing-site villages in the Tanga coastal area were sampled. These include Mwaboza to the north, Vyeru in the center, and Sahare to the south. At each transect, the first station was located close to the beach (around 100 m offshore). The study area was selected because of high catches in the small pelagic fishery, which are thought to be linked to the upwelling events that bring colder nutrient-rich water to the surface and promotes the growth of phytoplankton.

The study area (Fig.1) falls under the influence of a seasonal reversal of monsoon winds, which affect the weather and climate of the coastal areas of Tanzania and the Western Indian Ocean in general (Semba *et al.*, 2019). The change in wind speed and direction causes alternating northeast and southeast monsoon seasons. The northeast monsoon (NE) season, which usually begins in November and ends in March, is characterized by warmer waters, light rain, and weaker trade winds that prevail from the northeast (Richmond, 2002). Unlike the northeast, the southeast monsoon (SE), which starts in May and runs toward the end of September, has relatively heavy rainfall, cloudy conditions, cooler waters, strong wind speeds prevailing from the southeast (Richmond, 2002; Mahongo *et al.*, 2012).

The EACC also influences the physical dynamics of the Pemba Channel (Semba *et al.*, 2019). The current flows northward throughout the year with varied current speed depending on season. While the current has a mean velocity of about 50 cm $s^{-1}$ during the NE monsoon season, during the SE monsoon season the current flows at relatively higher speeds that reach 200 cm $s^{-1}$ (Mahongo and Shaghude, 2014; Semba *et al.*, 2019).

## Data collection

### *In-situ* data

During the field surveys, biological, physical and chemical variables were recorded. These included Chl-*a*, temperature, pH, Dissolved Oxygen (DO), nitrate-nitrogen (hereafter referred to as nitrate), phosphate and ammonium-nitrogen (hereafter referred to as ammonium). Four visits to the study area were undertaken in July 2016, September 2016, December 2016 and January 2017. These months were chosen for sampling because they fall within the SE (May to September) and NE (November to March) monsoon seasons. Three transects were selected in the study area and 10 points were sampled that were spaced at an interval of about 2 km apart (Fig. 1). This resulted in a total of 30 stations sampled during each visit, and 120 stations over the 4 visits. Various instruments were used to determine the hydrographic variables at each station: DO (Model 7031), pH and temperature (Hanna Instruments, Combo pH and EC), and salinity (Extech RF 20). Water samples for ammonium, phosphate and nitrate were collected for analysis in the laboratory.

A geographical positioning system (GPS) instrument was used to mark and record the exact position (longitude and latitude) of the stations. All physical, biological and chemical variables were measured or collected at the surface of the ocean, within the upper 30 cm of the water column.

Water samples collected for chlorophyll determination were filtered through 0.45$\mu$m membrane filters using a vacuum pump. The filters were stored frozen at a temperature of -20 °C for later analysis. In the laboratory, the filters were soaked in 10 ml of 90 % acetone overnight at 4 °C for extraction of Chl-*a*. The samples were centrifuged for 10 minutes at 4000 rpm and the supernatant was decanted into a clean test tube. The concentration of Chl-*a* was calculated as per Parsons *et al.* (1984). A portion of filtered water that was used for nutrient analysis was kept frozen at -20 °C. During laboratory analysis of respective nutrients, the samples were defrosted at room temperature and a portion of 300 ml was used. Laboratory analysis for nitrate, phosphate and ammonium followed standard methods as explained in Parsons *et al.* (1984). A spectrophotometer (UV 1601–Shumadzu Cooperation, Tokyo, Japan) was used to measure the absorbance of Chl-*a*, nitrate, phosphate and ammonium in the samples.

### Satellite Observations

The Moderate Resolution Imaging Spectroradiometer (MODIS) level–3 sea surface temperature, and the eight-day composite Chl-*a* concentration with spatial resolution of 4 km acquired between January 2015 and December 2018, were downloaded from ERDDAP at the Environmental Research Division of the National Oceanic and Atmospheric Administration server (Simons and Mendelssohn, 2012). Both gridded and

**Table 1.** Summary statistics in Chl-*a* concentration (mg m$^{-3}$) during the NE and the SE monsoon seasons in the Pemba Channel.

| | Descriptive statistics | | | | |
|---|---|---|---|---|---|
| **Season** | Minimum | Maximum | Mean | SD | Median |
| **NE** | 0.852 | 2.378 | 1.391 | 0.378 | 1.442 |
| **SE** | 0.897 | 2.486 | 1.243 | 0.273 | 1.191 |

tabular data of SST and Chl-*a* concentration within the study area were downloaded. To examine spatial and temporal differences in SST and Chl-*a* variability within the study area, the geographical extent of the area was defined using the minimum and maximum longitude and latitude values (Fig. 1).

The SST anomaly for each month at a given pixel was calculated as follows: First, the monthly spatial distribution of SST was computed from January 2015 to December 2018. This produced a 12-monthly averaged SST. Then, the SST anomaly along the latitudinal gradients was computed by subtracting the SST value from each grid with the mean SST along that latitude.

## Data processing and analysis

Once all the data were gathered, they were arranged and formatted in a structure for analysis and visualization using the Tidyverse Ecosystem Package (Wickham, 2017) in R language and environment for statistical computing (R Core Team, 2019). The data were visualized and tested for normal distribution (Millard, 2013). Variables that failed to meet the normal distribution assumptions were transformed using either log or square root. The distributed data were assessed using skewness to determine the transformation method. Those variables with skewness values which ranged between 0.5 and 1 were transformed using logarithm base 10, and those with skewness greater than 1 were transformed with square root. The normal distribution patterns of both original and transformed data were tested using the Shapiro-Wilk test. The data were found not to be normally distributed and unfit for parametric analysis, even after transformation. Thus, alternative non-parametric tests for statistical analysis were used.

The Wilcoxon test was used to test the difference in Chl-*a* concentration between the northeast and the southeast monsoon seasons. The difference in Chl-*a* concentration among sites was tested using the Kruskal-Wallis test. The influence of physical and chemical variables on Chl-*a* concentration was modeled using the Generalized Additive Model (GAM). GAM was selected as a multiple correlation analysis because it is a non-linear model capable of better capturing the effects of covariates on the dependent variables with non-normal distributions. Prior to carrying out the GAM, physical and chemical variables were tested for collinearity using the Durbin Watson Test() of the a Car package (Fox and Weisberg, 2019), and vif(), vifstep(), vifcor() of the USDM package (Naimi *et al.*, 2014). These calculate variance inflation factors (VIF) for physical-chemical variables and exclude highly correlated variables from the set through a stepwise procedure (Naimi *et al.*, 2014). There was no variable with a strong linear relationship with other variables, therefore all physical-chemical variables were used in the model. To map the spatial and temporal variation in Chl-*a* and the potential for upwelling in an area, the data were converted from 'data frame' to 'simple feature' that holds the spatial aspect.

Once the data were structured, the seasonal variation in chlorophyll from the *in–situ* data at the three transects was computed. Potential areas for upwelling within the study area from MODIS sea surface temperature was determined, and then the temperature anomalies were extracted at each station along the transects. The results of the temporal variation in Chl-*a* within the study sites was mapped with a heatmap. Maps were also used to represent the estimated development of potential areas for upwelling within the Pemba Channel and how they vary in both space and time. The ggplot (Wickham, 2016) and metR (Campitelli, 2019) packages were used to visualize and present results in maps.

## Results

### Spatial and seasonal vriation in Chl-*a*

Concentration of *in–situ* Chl-*a* measured along transects varied with seasons. While the Chl-*a* concentration during the SE monsoon ranged from 0.89 to 2.49 mg m$^{-3}$ with an overall mean of 1.24 ± 0.27 mg m$^{-3}$, concentration in the NE monsoon ranged from 0.85 to 2.38 mg m$^{-3}$ with an overall mean of 1.39 ± 0.38 mg m$^{-3}$ (Table 1). Although the minimum and maximum Chl-a

**Table 2.** Mean and standard deviation of Chl-*a* concentration values (mg m$^{-3}$) from *in-situ* and MODIS satellite data during the NE and SE monsoon seasons for 3 transects in the Pemba Channel.

| | Monsoon season | | | |
|---|---|---|---|---|
| | NE (Mean ± SD) | | SE (Mean ± SD) | |
| **Transect** | ***In-situ*** | **MODIS** | ***In-situ*** | **MODIS** |
| Mwaboza | 1.29 ± 0.39 | 0.20 ± 0.00 | 1.26 ± 0.39 | 0.36 ± 0.05 |
| Sahare | 1.49 ± 0.43 | 0.16 ± 0.04 | 1.16 ± 0.11 | 0.73 ± 0.30 |
| Vyeru | 1.59 ± 0.31 | 0.57 ± 0.16 | 1.30 ± 0.16 | 0.50 ± 0.41 |

concentrations during the SE monsoon were higher compared to the NE monsoon, the median during the SE (1.19 mg m$^{-3}$) was relatively lower than that for the NE (1.44 mg m$^{-3}$) (Table 1). Furthermore, the Wilcoxon test showed that the difference in the median of Chl-*a* concentration between the SE and the NE monsoon seasons was significant ($W$ = 2216, p = 0.029).

During the NE monsoon Chl-*a* concentration at Vyeru ranged from 0.89 to 2.14 mg m$^{-3}$ with a median of 1.59 mg m$^{-3}$, which was slightly higher than that at Mwaboza (0.89 to 2.38 mg m$^{-3}$ and median of 1.29 mg m$^{-3}$) and Sahare (0.85 to 2.18 mg m$^{-3}$ and median 1.49 mg m$^{-3}$) (Fig. 2). Similarly, during the SE monsoon season, the median concentration at the Vyeru site was also slightly higher (1.30 mg m$^{-3}$) than at Sahare (1.16 mg m$^{-3}$) and Mwaboza (1.26 mg m$^{-3}$) (Fig. 2).

When all seasons were pooled together, the concentration of Chl-*a* at Vyeru site ranged from 0.89 to 2.14 mg m$^{-3}$ with a median concentration of 1.32 mg m$^{-3}$, which is slighter higher than the median concentration at Mwaboza (1.27 mg m$^{-3}$) and Sahare (1.16 mg m$^{-3}$) (Fig. 3). The Kruskal-Wallis test showed a significant difference in median Chl-*a* concentration between the 3 sites ($H_2$ = 6.059, p = 0.048) for the pooled data.

The values of Chl-*a* from both *in-situ* and satellite observations during the NE and SE monsoon seasons are shown in Table 2. From the satellite observations, the NE monsoon season had lower Chl-*a* values compared to the SE monsoon season (Fig. 4). It was found that while the *in-situ* data showed a higher Chl-*a* value during the NE season (Fig. 2), satellite observations showed an opposite pattern with higher Chl-*a* values during the SE monsoon season, when data for all transects are pooled together. This was observed for Mwaboza and Sahare but not for Vyeru which had a slightly higher Chl-*a* value during the NE (Table 2).

### Monthly variation in satellite sea surface temperature and chlorophyll-*a*

Satellite sea surface temperature varied between the NE and SE monsoon seasons. Figure 5a shows warm water during the NE (November to March) and cooler water during the SE monsoon season (May to September). The warmest water was observed between February and April with a temperature above 30 °C (Fig. 5a).

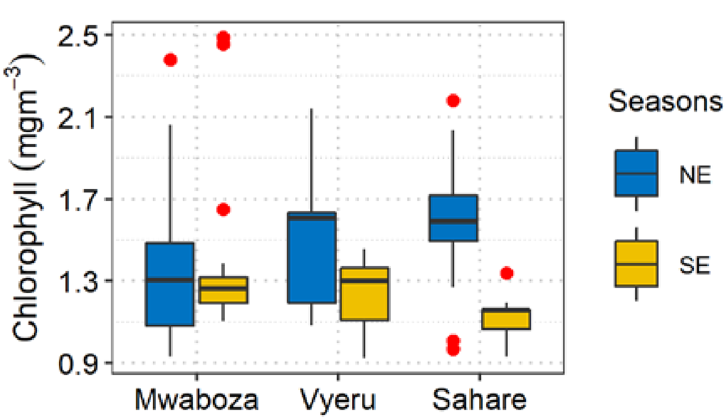


**Figure 2.** Chl-*a* concentration variation at Mwaboza, Sahare and Vyeru sites during the NE and SE monsoon seasons.

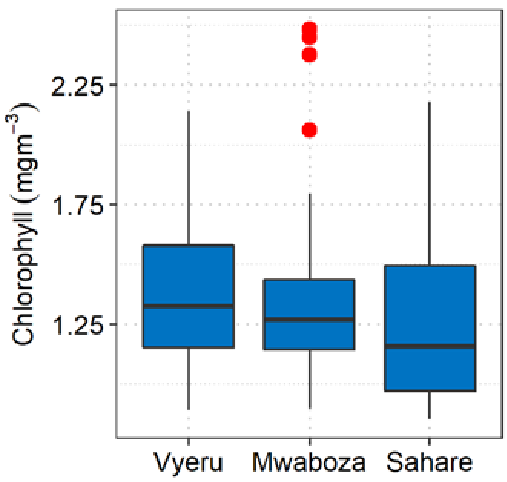


**Figure 3.** *In-situ* Chl-*a* variation at Vyeru, Mwaboza and Sahare with all seasons pooled together.

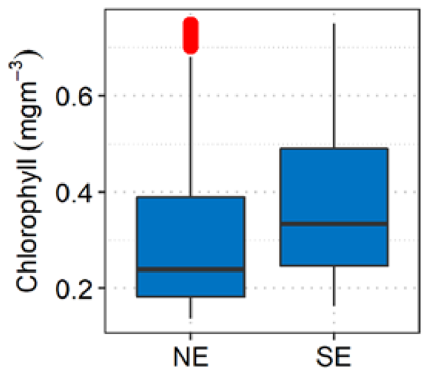


**Figure 4.** Satellite Chl-*a* concentration variation during the SE and the NE monsoon season within the study area.

Cooling is also observable during the SE monsoon season with the coolest water (below 27 °C) occurring in July and August (Fig. 5a). Concentration of satellite Chl-*a* varied (decreased) from the coast in an offshore direction throughout the study period (Fig. 5b).

## The SST anomaly

The monthly climatology of the MODIS SST anomaly from 2015 to 2018 during the NE monsoon season is shown in Figure 6. The main feature of the SST anomaly is the development of water with a relatively lower temperature (below 0 °C) than the mean during this season. The observed area of cold water below the mean (negative anomaly) is clearly visible and a common feature on the western side of the Pemba Channel during the NE monsoon season. This cold tongue of water develops during the NE monsoon season in November, reaches its peak in December, and starts to decay in March (Fig. 6).

The SST anomaly during the SE monsoon season is shown in Figure 7. The areas of water with temperature below the mean are absent during the southeast monsoon season. Unlike the NE monsoon season where a belt of water is formed with temperature below the mean on the western side of the Pemba Channel, this feature is absent during the SE monsoon season (Fig. 7).

Monthly anomalies for each sampling site along the Mwaboza, Vyeru and Sahare transects were obtained

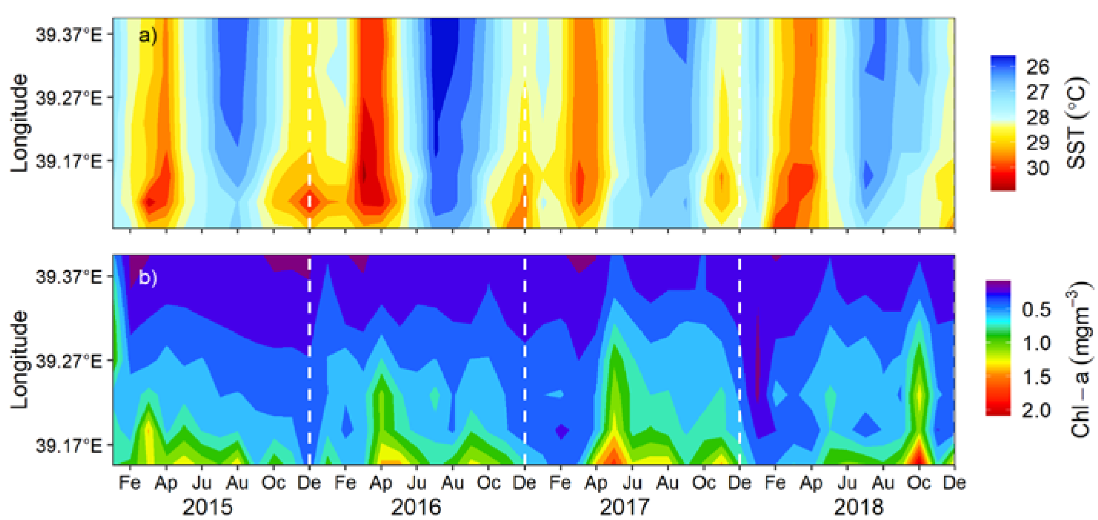


**Figure 5.** Monthly averaged longitude section hovmoler diagramme from satellite data: a) sea surface temperature, and b) satellite Chl-*a* concentration along the longitude between 5.1–4.64°S. White dotted line marks December—the last month of each year.

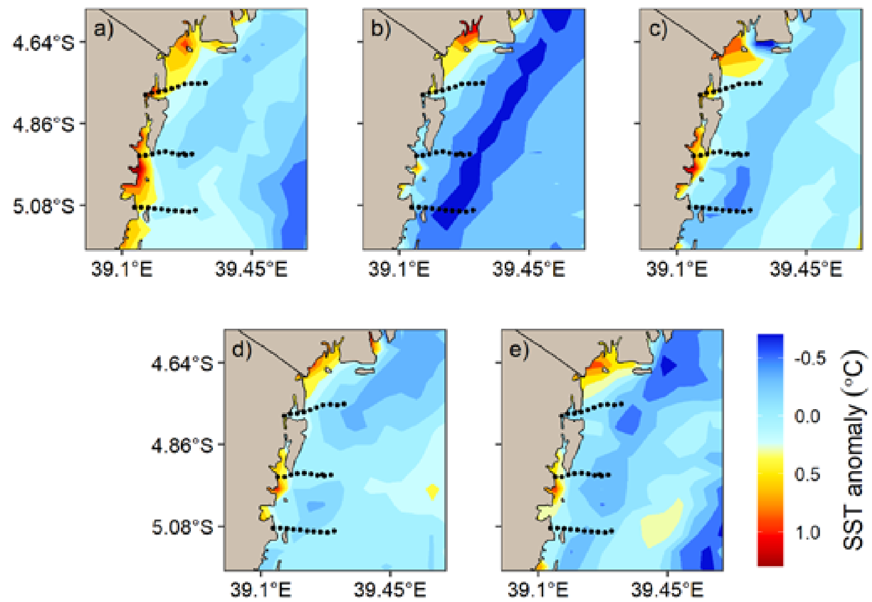


**Figure 6.** Climatological sea surface temperature anomalies for a) November, b) December, c) January, d) February, and e) March in the NE monsoon season.

by extracting the gridded anomaly of sea surface temperature (Fig. 8). While the SE monsoon season had a positive anomaly, the NE monsoon season showed a markedly negative anomaly. The anomaly showed similar seasonal patterns for stations sampled at Mwaboza (Fig. 8a), Vyeru (Fig. 8b) and Sahare (Fig. 8c).

### The surface Chl-*a* anomaly

The monthly climatology of the MODIS Chl-*a* anomaly from 2015 to 2018 during the SE monsoon season are shown in Figure 9. The main feature of the Chl-*a* anomaly is the presence of water patches with higher than average concentrations of Chl-*a* in the narrow coastal stretch, which is consistent throughout the season. The patch of above average Chl-*a* found along the northern transect is present from May to September (Fig. 9a–e). Another clear patch of above average Chl-*a* is found at the south of the southern transect of Sahare in May (Fig. 9a), June (Fig. 9b) and August (Fig. 9d), and unclear patches in July (Fig. 9c) and September (Fig. 9e).

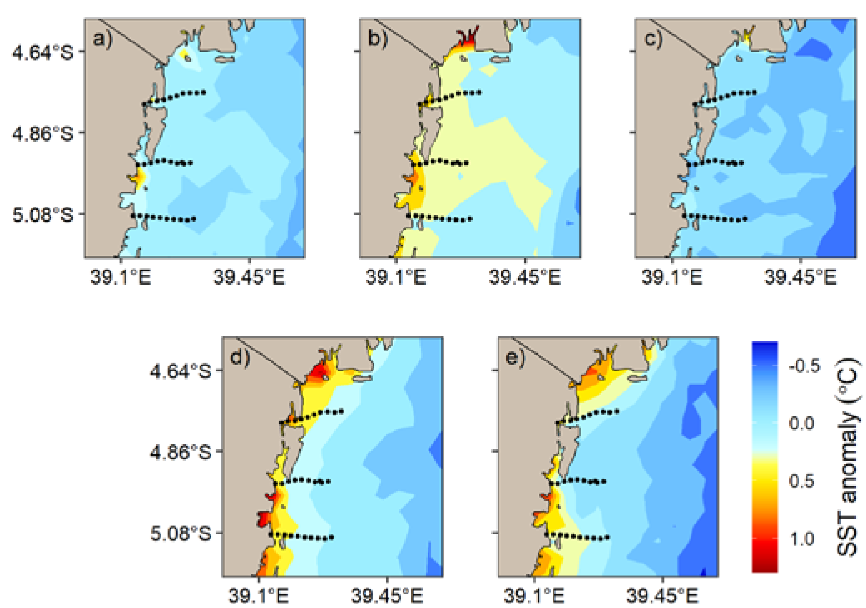


**Figure 7.** Climatological sea surface temperature anomalies for a) May, b) June, c) July, d) August, and e) September in the SE monsoon season.

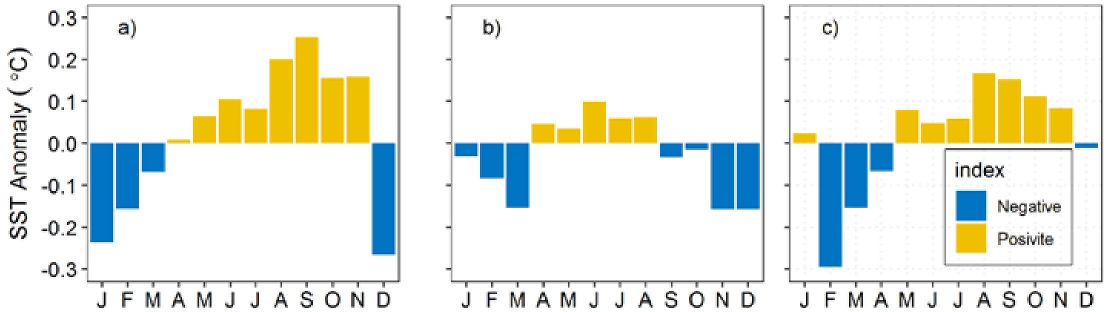


**Figure 8.** Seasonal cycles of computed sea surface temperature anomalies along three transects off Tanga. a) Mwaboza, b) Vyeru, and c) Sahare.

The patches of relatively higher than average Chl-*a* for the NE season months are shown in Figure 10. A clear patch is found north of the northern transect of Mwaboza throughout the 5-month period (Fig. 10a–e). The patches for the middle transect of Vyeru and the southern transect of Sahare are unclear during the NE monsoon season (Fig. 10).

## Influence of environmental variables

The influence of environmental variables on *in-situ* Chl-*a* concentration on the western side of the Pemba Channel was assessed using General Additive Models. Figure 11 shows the influence of chemical and physical variables. The results show that temperature, nitrate, ammonium and longitude have a significant negative influence on Chl-*a* (Fig. 11 a, d, f and g, Table 3), whereas phosphate showed an insignificant negative influence (Fig. 11e, Table 3). While pH showed a significant positive influence (Fig. 11b, Table 3), dissolved oxygen and latitude showed an insignificant positive influence on Chl-*a* (Fig. 11c and h, Table 3). Both latitude and longitude influence concentration of Chl-*a* independently. While the Chl-*a* value decreases with an increase in longitude, it increases with an increase in latitude. Chl-*a* decreases moving away from the coast, but also increases northward, though not significantly (Fig. 11g and h).

Linear and non-linear models were utilised to assess the influence of environmental variables (SST, DO, pH, ammonium, nitrate, phosphate) on seasonal differences in Chl-*a* concentration. Comparison of the performance of the two models is shown in Table 4. Model performance indices such as Akaike's Information Criteria (AIC), Bayesian Information Criteria (BIC) and Root Mean Square Error (RMSE) for GAM were

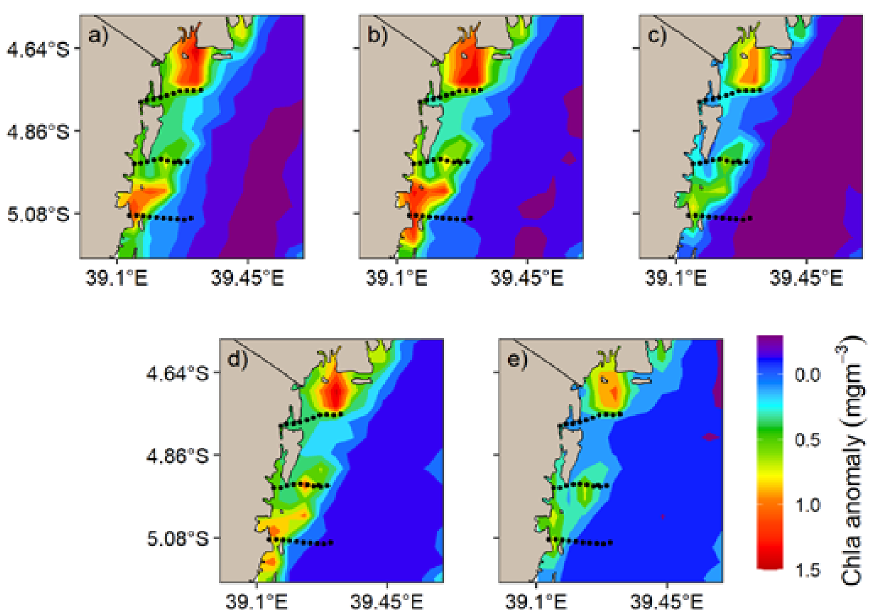


**Figure 9.** Climatological Chl-*a* concentration anomalies for a) May, b) June, c) July, d) August, and e) September in the SE monsoon season.

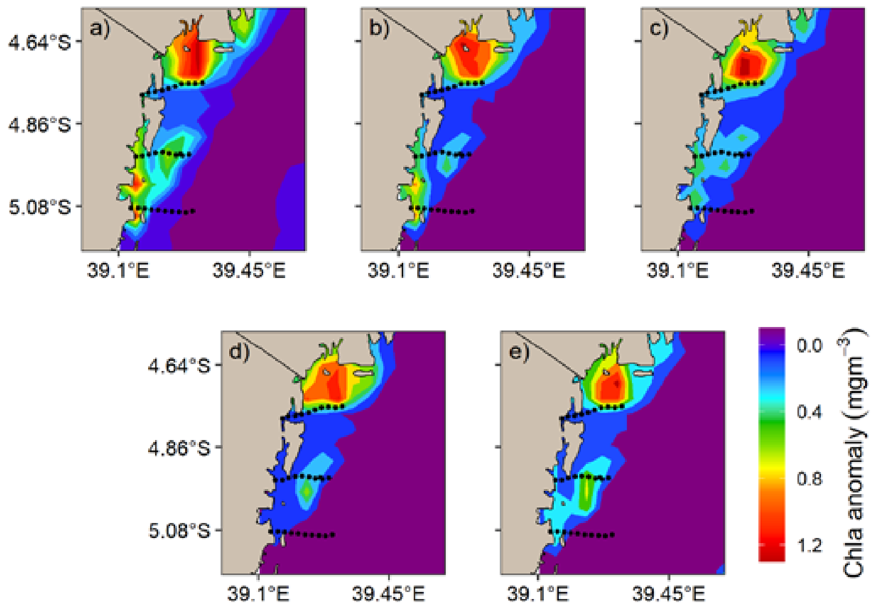


**Figure 10.** Climatological sea surface temperature anomalies for a) November, b) December, c) January, d) February, and e) March in the NE monsoon season.

lower compared to those obtained from the Linear Model (LM). This is further evidence that the GAM performed better than the LM for association between Chl-*a* concentration and environmental variables. Therefore, GAM was selected as the optimal model for comparing the influence of the environmental variables on Chl-*a* value during the NE and SE monsoon seasons.

The GAM was chosen to determine environmental variables that influence Chl-*a* variation with reversing monsoon regime. It was found that temperature, dissolved oxygen, nitrate, ammonium and longitude have a significant strong influence on Chl-*a* and accounts for about 78.7 % ($R^2$ = 0.787, p < 0.05) during the NE season (Table 5).

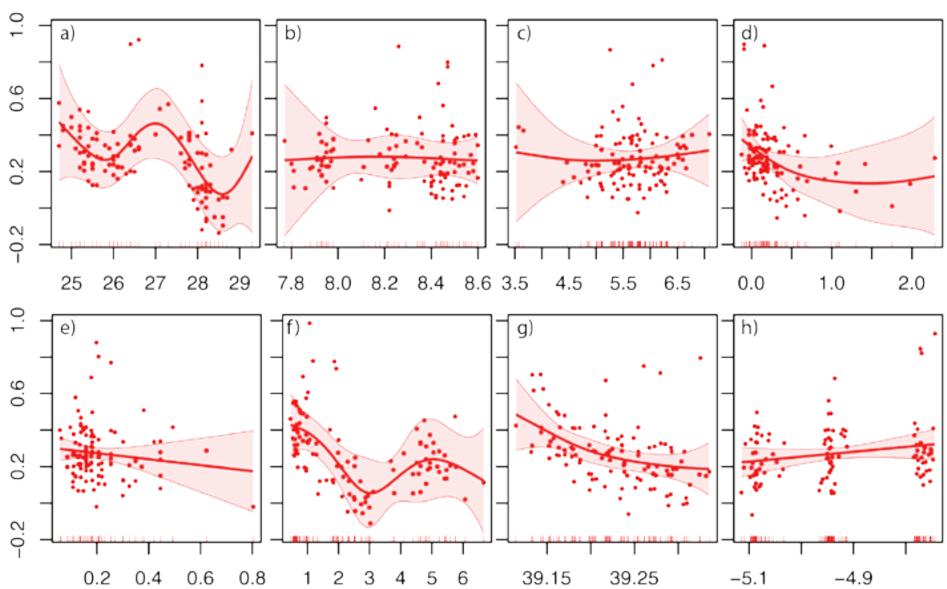


**Figure 11.** Residuals of the nonlinear terms estimated by means of GAM with smoothing splines for a) Temperature, b) pH, c) Dissolved Oxygen, d) Nitrate, e) Phosphate, f) Ammonium, g) Longitude, and h) Latitude.

**Table 3.** Summary statistics for the General Additive Model investigating factors influencing Chl-*a* concentration in the study area.

| | Statistics Values | | | |
|---|---|---|---|---|
| **Variable** | **Sum of square** | **Mean square** | **F** | **p** |
| Temperature. | 0.364 | 0.364 | 5.172 | 0.026 |
| pH | 0.456 | 0.456 | 6.478 | 0.013 |
| Dissolved Oxygen | 0.132 | 0.132 | 1.870 | 0.175 |
| Nitrate-N | 0.464 | 0.464 | 6.602 | 0.012 |
| Phosphate | 0.240 | 0.240 | 3.417 | 0.068 |
| Ammonium-N | 0.625 | 0.625 | 8.885 | 0.004 |
| Longitude | 0.504 | 0.504 | 7.160 | 0.009 |
| Latitude | 0.237 | 0.237 | 3.371 | 0.070 |

However, during the SE monsoon period, temperature, phosphate, ammonium and latitude showed strong and significant influence on Chl-*a* concentration, which accounted for 82.3 % ($R^2$ = 0.823, $p < 0.05$) (Table 6).

## Discussion

There is limited information on how environmental variables influence primary production in the Pemba Channel, particularly in coastal waters off Tanga Region. This study attempted to fill this information gap by using a non-linear model to determine the influence of physical and chemical variables on Chl-*a* concentration (as phytoplankton biomass). The study also determined the potential areas for coastal upwelling in the nearshore areas of the Pemba Channel and its influence on seasonal differences in phytoplankton concentration in the area. Several studies reported that the abundance and distribution of Chl-*a* in the coastal waters of Tanzania depend on monsoon seasons, with the NE period experiencing relatively low values in Chl-*a* compared to the SE season (Peter, 2013; Ezekiel, 2014; Semba *et al*., 2016; Moto and Kyewalyanga, 2017). Monsoon seasons play an important role as they have an influence on air and water temperature, wind and rainfall (Richmond, 2002). Changes in the wind patterns also impact the circulation and the direction of the coastal currents that might cause downwelling or upwelling. In addition, rainfall is often associated with input of nutrients from land-based sources. Such changes in the physical processes affect the distribution of nutrients and biological processes as well as marine organisms, particularly phytoplankton, resulting in the variation in Chl-*a* concentration.

While previous studies found higher values of Chl-*a* during the SE monsoon season (Peter, 2013; Ezekiel, 2014; Semba *et al*., 2016; Moto and Kyewalyanga, 2017), this study found the opposite where the NE monsoon season had relatively higher Chl-*a* concentration than the SE monsoon season (Fig. 2). The median Chl-*a* concentration of 1.44 mg $m^{-3}$ in the NE season compared to the value in the SE (1.19 mg $m^{-3}$) was significant (W = 2216, $p$ = 0.029). The difference in the Chl-*a* concentration between this study and previous studies could be explained by spatial rather than temporal variability. For instance, Peter (2013) as well as Moto and Kyewalyanga (2017) sampled in different locations,

**Table 4.** Performance comparison of the LM and GAM on the influence of environmental variables on Chl-*a* concentration.

| | Model Performance Indices | | | |
|---|---|---|---|---|
| Model | $R^2$ | AIC | BIC | RMSE |
| LM | 0.252 | 65.253 | 92.437 | 0.296 |
| GAM | 0.590 | 50.058 | 79.962 | 0.221 |

**Table 5.** Summary statistics for GAM investigating factors influencing Chl-*a* concentration during the NE monsoon season.

| | Statistics Values | | | |
|---|---|---|---|---|
| **Variable** | **Sum of square** | **Mean square** | **F** | **p** |
| Temperature | 1.008 | 1.008 | 13.400 | 0.001 |
| pH | 0.026 | 0.026 | 0.345 | 0.562 |
| Dissolved Oxygen | 0.386 | 0.386 | 5.131 | 0.032 |
| Nitrate | 0.602 | 0.602 | 8.008 | 0.009 |
| Phosphate | 0.167 | 0.167 | 2.214 | 0.149 |
| Ammonium | 0.700 | 0.700 | 9.303 | 0.005 |
| Longitude | 0.328 | 0.328 | 4.361 | 0.047 |
| Latitude | 0.121 | 0.121 | 1.607 | 0.217 |

although within Tanzanian waters. While Peter (2013) sampled in the coastal waters near the Pangani estuary, Moto and Kyewalyanga (2017) sampled in Zanzibar coastal waters, and the sampling in the present study took place in Tanga coastal waters.

Different locations could have differing physical processes that influence phytoplankton abundance. Higher Chl-*a* concentration during the SE season was attributed to strong winds that mix up nutrients from the bottom waters as well as nutrient input through coastal runoff, including sewage (Moto and Kyewalyanga, 2017). The other reason that can explain the difference in the concentrations between the present study and previous studies is the mismatch in the frequency of sampling. During the NE monsoon, the prevailing wind systems lead to coastal upwelling along the sampled transects of Sahare, Vyeru and Mwaboza areas in Tanga. The coastal waters around Tanga showed an upwelling signal during the NE monsoon season, resulting in higher Chl-*a* concentration compared to the SE season. This phenomenon supports fisheries productivity with the pelagic fishery catches in the area being higher during the NE season than in the SE season, possibly being driven by high Chl-*a* values.

The upwelling areas of coastal of Tanzania are poorly understood. To attempt to understand the observed Chl-*a* values in the study area, monthly temperature anomalies in SST were applied as a proxy to upwelling signals. The result of the seasonal temperature anomalies clearly indicates a formation of permanent cold water in the coastal water of the western side of the Pemba Channel during the NE monsoon season (Fig. 6). During the SE monsoon, the winds exert a generally

**Table 6.** Summary statistics for GAM investigating factors influencing Chl-*a* concentration during the SE monsoon season.

| | Statistics Values | | | |
|---|---|---|---|---|
| **Variable** | **Sum of square** | **Mean square** | **F** | **p** |
| Temperature | 0.281 | 0.281 | 7.982 | 0.010 |
| pH | 0.012 | 0.012 | 0.338 | 0.567 |
| Dissolved Oxygen | 0.072 | 0.072 | 2.053 | 0.167 |
| Nitrate | 0.002 | 0.002 | 0.058 | 0.812 |
| Phosphate | 0.277 | 0.277 | 7.880 | 0.011 |
| Ammonium | 0.375 | 0.375 | 10.659 | 0.004 |
| Longitude | 0.005 | 0.005 | 0.149 | 0.704 |
| Latitude | 0.588 | 0.588 | 16.704 | 0.001 |

northward stress over nearly the entire surface area of the Western Indian Ocean including in the study area (Semba *et al.*, 2019). However, during the NE monsoon, which occurs from October to March, the wind pattern in the coastal waters of Tanzania reverses to exert a generally southward stress on the ocean surface. This causes Ekman transport of surface waters in the opposite direction to the wind stress (90° to the left rather than to the right) which is directed offshore from the coast (i.e. in the direction favorable for upwelling) during the NE monsoon.

The surface temperature anomaly is roughly comparable and has quite similar seasonal cycles off the coast of Tanga (Fig. 8). The substantial offshore Ekman transport occurring in this part of the ocean during the NE monsoon are, in fact, dwarfed by the more intense offshore Ekman transport of the SE monsoonal period. This may deepen the thermocline and nutricline near this coast during the SE monsoon to such an extent that it prevents upwelling due to the less intense offshore transport. The patterns of monthly anomalies derived from SST anomalies used as an indicator for potential months for upwelling in Figure 8 show clearly that the NE season experiences colder water compared to the SE season. This result matches the upwelling indices derived from climatological winds (Bakun *et al.*, 1998). However, it should be mentioned that anomalies found in this study are based on coarsely-spaced satellite observations to describe the potential months and areas for upwelling. Thus, inferences as to the actual upwelling that may occur in response to these patterns should, at this point, be regarded as hypothetical.

It was found that surface water during the NE was warmer than during the SE monsoon season (Fig. 5a). However, the coastal upwelling that occurs along the Eastern African coast during the NE monsoon season partly explains the observed high Chl-*a* value during this season. The formation of cold water might be caused by coastal upwelling that brings cooler and nutrient rich water to the surface. Consequently, phytoplankton growth is stimulated, and this is used as a primary food for pelagic fish like mackerel and anchovies that are caught in abundance during this season. This also supports the results obtained in this study, where the values of Chl-*a* in this area were found to be relatively higher during the NE monsoon than in the SE monsoon season. The weak winds and current speed also increase the residence time of the cold and nutrient rich water in the area and hence allow phytoplankton growth and reproduction, as evidenced by higher Chl-*a* concentration. In the present study, although anomaly indices from SST were able to be computed from satellite data, information on water temperature below the surface is still lacking.

Similar to Peter *et al.* (2018), it was also found that the influence of environmental variables on Chl-*a* variation depends on season. The NE monsoon showed a strong and significant association of environmental variables with Chl-*a* of about 79 % ($R^2 = 0.79$, $p < 0.05$). It was identified that, in general, the main physico-chemical variables that influenced Chl-*a* concentration were ammonium, nitrate, phosphate, pH and dissolved oxygen. Although other variables contributed to this association, temperature, dissolved oxygen, nitrate, ammonium and longitude had the strongest influence. Similar to during the NE season, the SE season values of Chl-*a* were influenced by temperature and ammonium too. Phosphate and latitude, which showed weak influences during the NE period, indicated a strong and significant association during the SE period ($R^2 = 0.82$, $p < 0.05$). However, the amount of dissolved oxygen at the surface can be affected by oxygen saturation in the air which might also impact on the results obtained.

It was also noted that a small difference between sites resulted into differences in variables that contributed significantly to changes in Chl-*a*, at a given site and season. It is suspected that Vyeru could be the epicenter of upwelling. High concentration of nutrients at Vyeru was revealed by the principal component analysis which showed ammonium, phosphate, dissolved oxygen and pH as being the major influence on Chl-*a* concentration during the NE monsoon season.

## Conclusion

The present study conducted in the Pemba Channel, offshore of Tanga Region, assessed the main drivers influencing levels of phytoplankton biomass (as Chl-*a* concentration) in the SE and NE monsoon seasons. Sampling transects conducted at Sahare, Vyeru and Mwaboza sites showed that each site had different hydrographic characteristics, which resulted in significant variations in Chl-*a* concentrations, although the sites were only about 20 km apart from each other. It was found that Chl-*a* concentration was significantly higher during the NE monsoon as compared to the SE monsoon period, and this difference is linked to higher nutrient concentrations during the NE season, mostly probably due to seasonal upwelling in the area. It was identified that, in general, the main physico-chemical variables that positively influenced Chl-*a* concentration were ammonium, nitrate, phosphate, temperature and dissolved oxygen. This study was a preliminary step, carried out for discrete months (only 2 per seasons), and 4 years of satellite SST measurements were considered. To get a better understanding of the observed site-specific and season-specific variations, it is recommended that more *in-situ* data should be collected and linked to satellite derived Chl-*a* measurements, to provide broader spatial and temporal coverage of the study area. It is further suggested that studies of both phytoplankton and zooplankton community composition at the study sites are required to better understand which factors favour which plankton group, and how this is linked to productivity in the small pelagic fisheries.

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## References

Bakun A, Roy C, Lluch-Cota, S (1998) Coastal upwelling and other processes regulating ecosystem productivity and fish production in the Western Indian Ocean. In: Sherman K, Okemwa EN, Ntiba MJ (eds) Large marine ecosystems of the Indian ocean: assessment, sustainability and management. Londres : Blackwell. pp 103-141

Barlow R, Kyewalyanga M, Sessions H, Van den Berg M, Morris T (2008) Phytoplankton pigments, functional types, and absorption properties in the Delagoa and Natal Bights of the Agulhas ecosystem. Estuarine, Coastal and Shelf Science 80 (2): 201-211

Barlow R, Lamont T, Kyewalyanga M, Sessions H, Van den Berg M, Duncan F (2011) Phytoplankton production and adaptation in the vicinity of Pemba and Zanzibar Islands, Tanzania. African Journal of Marine Science 33 (2): 283-295

Bouman HA, Platt T, Sathyendranath S, Li WK, Stuart V, Fuentes-Yaco C (2003) Temperature as indicator of optical properties and community structure of marine phytoplankton: Implications for remote sensing. Marine Ecology Progress Series 258: 19-30

Campitelli E (2019) MetR: Tools for easier analysis of meteorological fields [https://CRAN.R-project.org/package=metR]

Duarte CM, Cebrián J (1996) The fate of marine autotrophic production. Limnology and Oceanography 41 (8): 1758-1766

Ezekiel J (2014) Temporal and spatial variation of phytoplankton in Rufiji Delta/Mafia Channel, southern Tanzania. MSc Thesis, University of Dar es Salaam, Dar es Salaam, Tanzania. 97 pp

Field CB, Behrenfeld MJ, Randerson JT, Falkowski P (1998) Primary production of the biosphere: Integrating terrestrial and oceanic components. Science 281 (5374): 237-240

Fox J, Weisberg S (2019) An R companion to applied regression (Third). Sage, Thousand Oaks CA [https://socialsciences.mcmaster.ca/jfox/Books/Companion/]

Gallienne CP, Smythe-Wright D (2005) Epipelagic mesozooplankton dynamics around the mascarene plateau and basin, southwestern Indian Ocean. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 363 (1826): 191-202

Gröniger A, Sinha R, Klisc M, Häder, DP (2000) Photoprotective compounds in cyanobacteria, phytoplankton and macroalgae – a database. Journal of Photochemistry and Photobiology B: Biology 58 (2-3): 115-122

Kyewalyanga, M (2002) Spatial-temporal changes in phytoplankton biomass and primary production in Chwaka Bay, Zanzibar. Tanzania Journal of Science 28 (2): 11-26

Kyewalyanga M (2015) Phytoplankton primary production. In: Paula J (ed) The regional state of the coast report: Western Indian Ocean. UNEP-Nairobi Convention-WIOMSA. pp 213-230

Lamont T, Barlow R (2015) Environmental influence on phytoplankton production during summer on the Kwazulu-natal shelf of the Agulhas ecosystem. African Journal of Marine Science 37 (4): 485-501

Lee DB, Song HY, Park C, Choi KH (2012) Copepod feeding in a coastal area of active tidal mixing: Diel and monthly variations of grazing impacts on phytoplankton biomass. Marine Ecology 33 (1): 88-105

Limbu S, Kyewalyanga M (2015) Spatial and temporal variations in environmental variables in relation to phytoplankton composition and biomass in coral reef areas around Unguja, Zanzibar, Tanzania. Springer Plus 4. 646 pp

Mahongo S, Francis J, Osima S (2012) Wind patterns of coastal Tanzania: Their variability and trends. Western Indian Ocean Journal of Marine Science 10 (2): 107-120

Mahongo SB, Shaghude YW (2014) Modelling the dynamics of the Tanzanian coastal waters. Journal of Oceanography and Marine Science 5 (1): 1-7 [https: // doi.org/10.5897/JOMS2013.%200100]

Meyer A, Lutjeharms J, De Villiers S (2002) The nutrient characteristics of the Natal Bight, South Africa. Journal of Marine Systems 35 (1-2): 11-37

Millard SP (2013) EnvStats: An r package for environmental statistics. Springer, New York [http://www.springer.com]

Moto E, Kyewalyanga M (2017) Variability of chlorophyll-a in relation to physico-chemical variables in Zanzibar coastal waters. Advances in Ecological and Environmental Research 2 (12): 475-492

Naimi B, Hamm N, Groen, TA, Skidmore AK, Toxopeus AG (2014) Where is positional uncertainty a problem for species distribution modelling. Ecography 37: 191-203 [https://doi.org/10.1111/j.1600-0587.2013.00205.x]

Parsons T, Maita Y, Lalli C (1984) A manual of chemical and biological methods for seawater analysis. Marine Ecology Progress Series 199: 43-53

Peter N (2013) Phytoplankton distribution and abundance along Zanzibar and Pemba Channels. MSc Thesis, University of Dar es Salaam, Dar es Salaam, Tanzania. 104 pp

Peter N, Semba M, Lugomela C, Kyewalyanga MS (2018) The influence of physical-chemical variables on the spatial and seasonal variation of chlorophyll-a in coastal waters of Unguja, Zanzibar, Tanzania. Western Indian Ocean Journal of Marine Science 17 (2): 25-34

R Core Team (2019) R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria [https://www.R-project. org/]

Richmond MR (ed)(2002) A field guide to the seashores of eastern Africa and the western Indian Ocean Islands. 461 pp

Sá C, Leal M, Silva A, Nordez S, André E, Paula J, Brotas V (2013) Variation of phytoplankton assemblages along the Mozambique coast as revealed by hplc and microscopy. Journal of Sea Research 79: 1-11

Semba M, Kimirei I, Kyewalyanga M, Peter N, Brendonck L, Somers B (2016) The decline in phytoplankton biomass and prawn catches in the Rufiji-Mafia Channel, Tanzania. Western Indian Ocean Journal of Marine Science 15 (1): 15-29

Semba M, Lumpkin R, Kimirei I, Shaghude Y, Nyandwi N (2019) Seasonal and spatial variation of surface current in the Pemba Channel, Tanzania. PLoS One 14 (1): e0210303 [https://doi.org/10.1371/journal.pone.0210303]

Simons R, Mendelssohn R (2012) ERDDAP- a brokering data server for gridded and tabular datasets. AGU Fall Meeting Abstracts: IN21B-1473

Vargas CA, Escribano R, Poulet S (2006) Phytoplankton food quality determines time windows for successful zooplankton reproductive pulses. Ecology 87 (12): 2992-2999

Wickham H (2016) Ggplot2: Elegant graphics for data analysis. Springer-Verlag, New York [https://ggplot2.tidyverse.org]

Wickham H (2017) Tidyverse: Easily install and load the 'tidyverse' [https://CRAN.R-project.org/package=tidyverse 30]

# Employing multivariate analysis to determine the drivers of productivity on the North Kenya Bank and in Kenyan territorial waters

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## Abstract
A complex mix of natural processes exist in nearshore and offshore waters which influence coastal and marine ecosystem productivity. An understanding of the biogeochemical processes involved is a key element in interdisciplinary studies of primary production, oceanic flux and storage of carbon dioxide. Water circulation in the East African region is influenced by coastal currents driven by monsoon winds. There are four oceanic currents influencing Kenya's coastal waters; namely the East African Coastal Current, the Somali Current, the Southern Equatorial Current and the Equatorial Counter Current. The Kenyan fishing industry is slowly embracing offshore fishing grounds, and the North Kenya Bank is emerging as the next fishery frontier. This study aims to provide insight on the processes driving the productivity of Kenya's territorial waters. The variable Si* (the difference between available silicate [$Si(OH)_4$] and nitrate [$NO_3^-$ ]) was employed as a proxy of upwelling. It was highly positively correlated to chlorophyll-a, indicating that upwelling is a major phenomenon driving productivity in Kenyan territorial waters. Particulate Organic Carbon (POC) and Dissolved Oxygen (DO) exhibited a lesser positive correlation with chlorophyll-a, implying that remineralization also has some influence in the productivity of the area.

**Keywords:** Nitrate, Silicate, Productivity, Kenya, North Kenya Bank

## Introduction
The marine fishery within the East African region provides a critical source of food security and livelihoods to coastal communities, as is the case in many developing countries around the world (Fondo, 2004; Munga, 2013; Kiilu *et al.*, 2019; Le Manach *et al.*, 2015; Zeller *et al.*, 2014). The western Indian Ocean region has a rich fisheries resource presumed to be dependent on wind driven upwelling systems (Kiilu *et al.*, 2019). Coastal upwelling is often associated with increased productivity of both primary producers and small pelagic fishes (McClanahan, 1988). Johnson *et al.* (1982) postulated that the deflection of the East African Coastal Current (EACC) seawards at its point of convergence with the Somali Current (SC) is mainly due to topographic forcing on the North Kenyan Bank (NKB). Similarly, Gallienne and Smythe-Wright (2005) attributed the large levels of zooplankton biomass observed in the Mascarene Basin to the east, to topographic forcing causing turbulence, as the Plateau obstructs the flow of the South Equatorial Current (SEC). A study by Jacobs *et al.* (2020) further demonstrated that some degree of wind-driven coastal upwelling occurs along the wider Kenyan coastline every year during the months of the North East Monsoon (NEM).

Studies have associated abiotic and biotic factors with the productivity of a system. It has been reported that for about 90 % of the ocean surface, primary production at the euphotic layer is almost certainly limited

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by the supply of nutrients, especially nitrate (N) and (P) (Nifong and Silliman, 2017). Globally, nitrogen and phosphorus are the two elements that potentially limit the biologically mediated assimilation of carbon in the oceans by photoautotrophs. Consequently, a major part of primary production is considered to be supported by upwelling of deep waters rich in N and P (Broecker and Peng, 1972).

Studies conducted in Kenyan coastal waters by Jacobs *et al.* (2020) employing the NEMO (Nucleus for European Modelling of the Ocean) model with a biogeochemistry component represented by an embedded MEDUSA-2 model, postulated a water column-integrated primary production, with a maximum productivity rate of up to 1.5 g $C/m^{-2}$/day over the NKB, which was aligned with a high nutrient availability associated with upwelling. The SC and the EACC converge during the NEM, and flow away from the coast to form the SECC. This induces the upwelling of cold, nutrient-rich waters, which are brought up from the deep waters to the surface, resulting in the NKB being a highly productive area (Jacobs *et al.,* 2020). Enhanced upwelling events, associated with cool temperatures, result in elevated productivity.

In addition to nutrient availability, ocean productivity is to a large extent limited by physicochemical parameters; mainly temperature, salinity, and light (Lathuiliere *et al.,* 2011, Broecker and Peng, 1972). However, light penetration is not a limiting factor in the photic zone within the tropical region where consumption of nitrate by phytoplankton renders the sunlit ocean devoid of nitrate. Nitrate, however, increases rapidly with depth in the underlying region, where it is resupplied through the remineralization of organic matter (Broecker and Peng, 1972). Biogeochemical processes such as the production and decomposition of biogenic organic matter and the sinking of particulate matter determine the distribution of nutrients in the ocean (Hirose and Kamiya, 2003). The vertical supply of nitrate to the surface ocean depends not only on the vertical transport induced by dynamical processes like turbulent entrainment, Ekman pumping, and frontal and eddy-induced upwelling, but also on the vertical gradient of nitrate (Mahadevan, 2014; Omand and Mahadevan, 2015). Further, it depends on the depth from which nitrate needs to be drawn (Omand and Mahadevan, 2015).

The study area is relatively shallow (200-1500 m) and can be construed to experience faster nutrient replenishment due to the shorter migration distances from the sediment source. The area is however assumed to hold low nutrients due mainly to the high productivity associated with optimal physical parameters leading to high nutrient depletion, complicating the use of nutrients as a productivity proxy.

This study therefore seeks to employ a multivariate model to investigate the parameters that drive productivity within the study area by relating the concentration of chlorophyll-a with parameters presumed to enhance its production. Variation in primary productivity, measured typically as the concentration of *chlorophyll-a* in water, is a primary determinant of all biological productivity up the food web and trophic pyramid (Jacobs *et al.,* 2020; Weeks and Shillington, 1996; Lutjeharms, 1985).

## Materials and methods

### Study Area

The study site spans across the entire coastline encompassing the territorial waters of Kenya (Fig. 1). This region was presumed to experience high productivity due to wind driven upwelling systems. The territorial waters extend from a latitude of about 4.5 degrees South (towards the Tanzania boarder) to about 1.5 degrees South (towards the Somali boarder).

These areas experience the influence of the north flowing EACC (Fig. 2). The velocity of the EACC varies between 0.5 to 2 m/s, flowing more rapidly during the South East Monsoon (SEM) season and slower during the NEM season (Schott and McCreary, 2001; Swallow *et al.,* 1983; Swallow *et al.,* 1991).

During the NEM, the SC reverses and flows southward at speeds of 0.5–1 $ms^{-1}$ (Leetmaa *et al*., 1982; Molinari *et al*., 1990). It then meets the northward flowing EACC to form a confluence zone at 2–4°S, before the flow veers offshore as the eastward flowing SECC (Shenoi *et al*., 1999; Schott and McCreary, 2001; Schott *et al*., 2009). This offshore flow leads to divergence at the coast. To ensure continuity of mass, the flow results in the upwelling of cold, nutrient-rich deeper waters (Kabanova, 1968; Liao *et al*., 2017).

## Methodology

Water samples were collected within the territorial waters of Kenya in the month of January, 2017 at the stations indicated in Fig. 1. The samples were collected from the RV Mtafiti with Niskin bottles at depth intervals of 20m to a maximum depth of

300 m. Physicochemical parameters were measured using a Sea-Bird CTD (SBE 19 plus V2 SeaCAT CTD) equipped with a SBE 63 Optical dissolved oxygen Sensor, and a SBE 27 pH/O.R.P pH meter. Temperature was measured in ITS-90 degrees Celsius (°C), while the measure of conductivity, temperature, and pressure provided for the calculation of the amount of dissolved salts in the water – the salinity. were obtained by filtering a 3 l water sample through glass fiber (GF/F) filters pre-combusted in a muffle furnace for 4 hours at 500 °C, and the filtrate stored at -20 °C to await analysis. Three litre samples for chlorophyll-a analysis were collected in pre-rinsed plastic bottles and filtered under vacuum onto 25mmWhatman GF/F (glass fibre filter) paper (Parsons *et al.,* 1984). The filtrate on the filter papers were enclosed in alu-

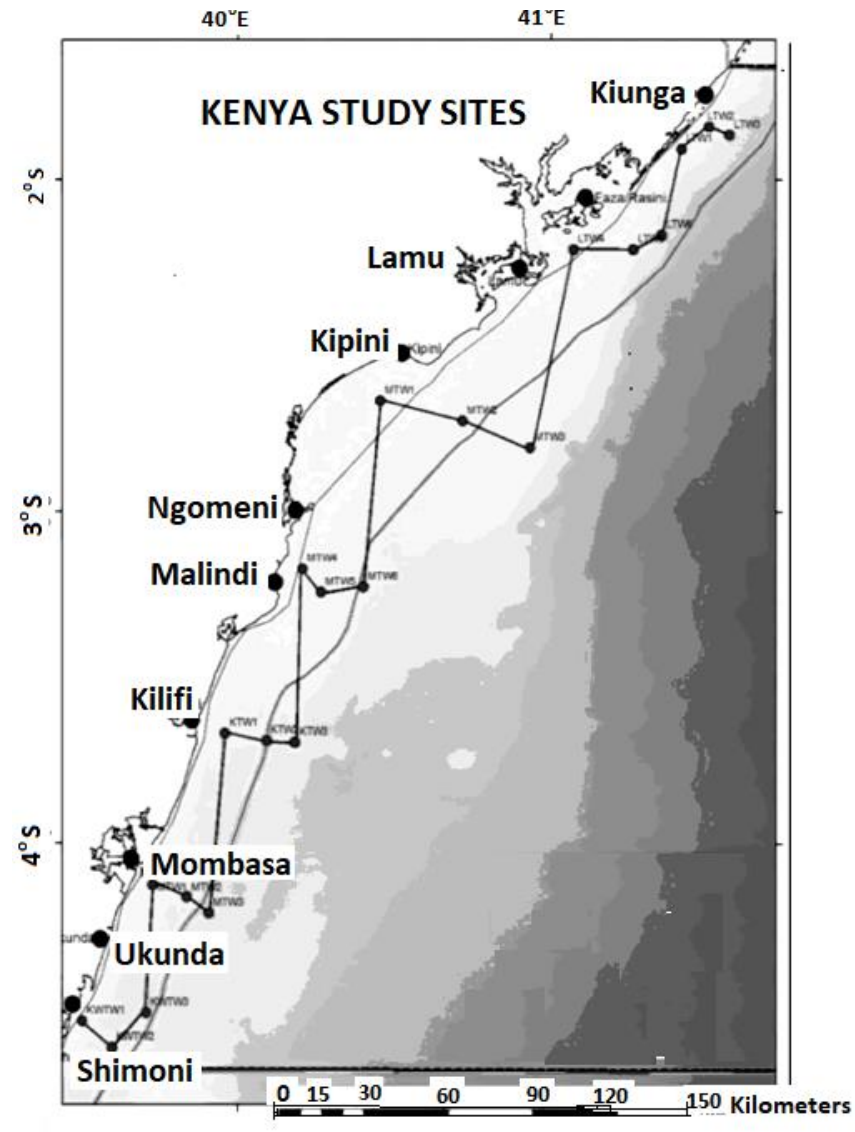


**Figure 1.** Map showing the sampling sites within Kenyan territorial waters.

Quality control on dissolved oxygen (DO) measurements was carried out using a representative sample for DO and the Winkler method (Parsons *et al.*, 1984).

Nutrient samples were collected in 100 ml polyethylene bottles pre-rinsed in 10 % HCl, after which the samples were stored in a freezer awaiting analysis in the laboratory. Particulate organic carbon samples minium foil pouches and frozen to await analysis in the laboratory. Chlorophyll-a was measured on a spectrophotometer (Thermo Fisher Scientific Model Genesys 10S; USA make) after extraction in 90 % acetone. Nutrient samples were analysed in the laboratory using a four-channel auto-analyzer (Seal QUAATRO Auto Analyzer), while Particulate Organic Carbon (POC) samples were analyzed through the dichromate

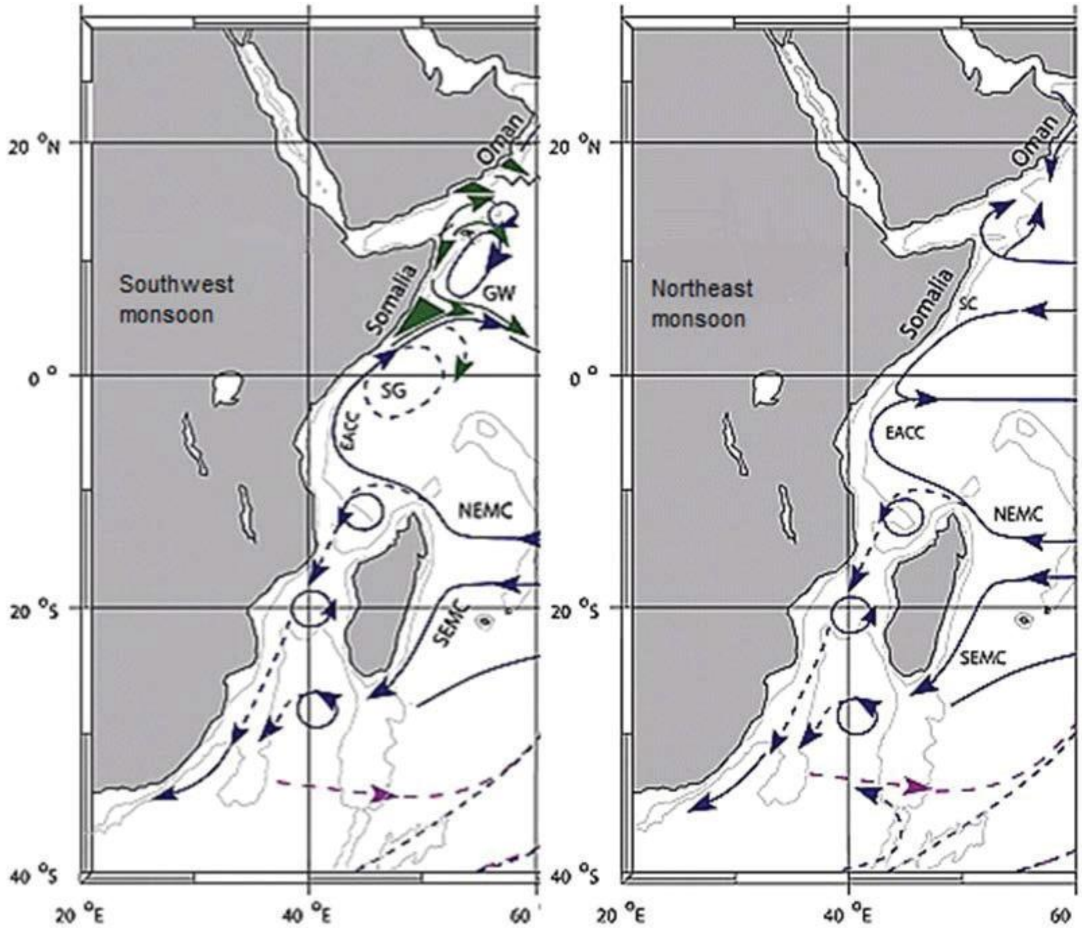


**Figure 2.** Schematic representation of identified current branches during the southwest and northeast monsoons in the western Indian Ocean region. Current branches shown include the South Equatorial Current (SEC), South Equatorial Counter Current (SECC), Northeast and Southeast Madagascar Current (NEMC and SEMC), East African Coastal Current (EACC), Somali Current (SC), Southern Gyre (SG) and Great Whirl (GW), Southwest and Northeast Monsoon Currents (SEMC and NEMC) (Adapted from Schott *et al*., 2009)

redox colorimetric method. The dichromate redox colorimetric method utilizes the formation of the green Cr III species resulting from the reduction of the orange dichromate (Cr VI) species. The amount of dichromate consumed is determined against a set of standards and measured on a spectrophotometer in the visual range.

## Statistical analysis

The data was analysed statistically using Statistica 8.0 software. Variables with values above 10 were log transformed to normalize the data. Principle component analysis was the multivariate method of choice. In principle component analysis (PCA), straight lines are sought that best fit the clouds of points in the vector spaces (of variables and cases), according to the least squares criterion. This in turn yields the principal components (factors) that result into the maximum sums of squares for the orthogonal projections. Consequently, a lower dimensional vector subspace is recovered, that represents the original vector space (Miranda *et al.,* 2008). Factor coordinates of the variables also referred to as 'factor loadings' are the correlations between the variable and the factor axes. Mathematically speaking, a principal component is a linear combination of the variables that are most correlated with that component. The first factor holds a higher correlation between the variables than the second factor does. This is to be expected because these factors are extracted successively and will account for less and less variance overall (Miranda *et al.*, 2008).

Mean subtraction ("mean centering") is necessary for performing PCA to ensure that the first principal component describes the direction of maximum variance. If mean subtraction is not performed, the first principal component will instead correspond to the mean of the data. A mean of zero is needed for finding a basis that minimizes the mean square error of the approximation of the data (Miranda *et al.*, 2008) Assuming zero empirical mean (the empirical mean of the distribution has been subtracted from the data set), the principal component $w_1$ of a data set x can be defined as:

$$\mathbf{w}_1 = \underset{\|\mathbf{w}\|=1}{\arg\max}\, \mathrm{Var}\{\mathbf{w}^T\mathbf{x}\} = \underset{\|\mathbf{w}\|=1}{\arg\max}\, E\left\{\left(\mathbf{w}^T\mathbf{x}\right)^2\right\}$$

## Results and discussions

Multivariate analysis was employed to identify the oceanographic parameters influencing the productivity in the study area as well as to capture the influencing biogeochemical processes. The data was analysed by PCA using Statistica 8.0 software and is presented as a projection of variables on factor-planes, as factor coordinates of variables, and as 3D surface plots (Fig. 3 to 6; Table 1). PCA allows summarising and visualisation of the information in a space containing observations described by multiple inter-correlated quantitative variables. Thus, PCA extracts the important information from a multivariate data table and generates a set of fewer new variables called 'principal components/factor axis'. The information in a given data set corresponds to the 'total variation' it contains. The goal of PCA is to identify directions (or principal components) along which the variation in the data is maximal. In the PCA model a zero loading means that the variable does not contribute to the component shown. The uniqueness of a variable is described by values near 1.0, indicating variables that are tending to measure unique properties in the data set.

Figure 3 presents a projection of variables on the 1x2 factor-plane; the variables on the factor coordinates are in reference to their relation to the grouping variable chlorophyll-a. Employing chlorophyll-a as a grouping variable enables the PCA to relate all the variables relative to chlorophyll-a. Factor axis 1 describes 27 % of the interaction of chlorophyll-a with the measured variables.

Biogeochemical processes provide key information in a study area and can be applied to understand the processes influencing productivity of a system. The ocean is expansive and the use of models and proxies helps researchers to better understand the functioning of a system. Signatures that indicate deep water influx/upwelling are important in understanding productivity drivers. The current study employed Si* (the difference between available silicate [Si(OH)4] and nitrate [$NO_3^-$ ] to study upwelling. Sarmiento *et al.* (2004) used Si* as a tracer of the return path of deep waters upwelled into the thermoclines of ocean systems. The rational is that when

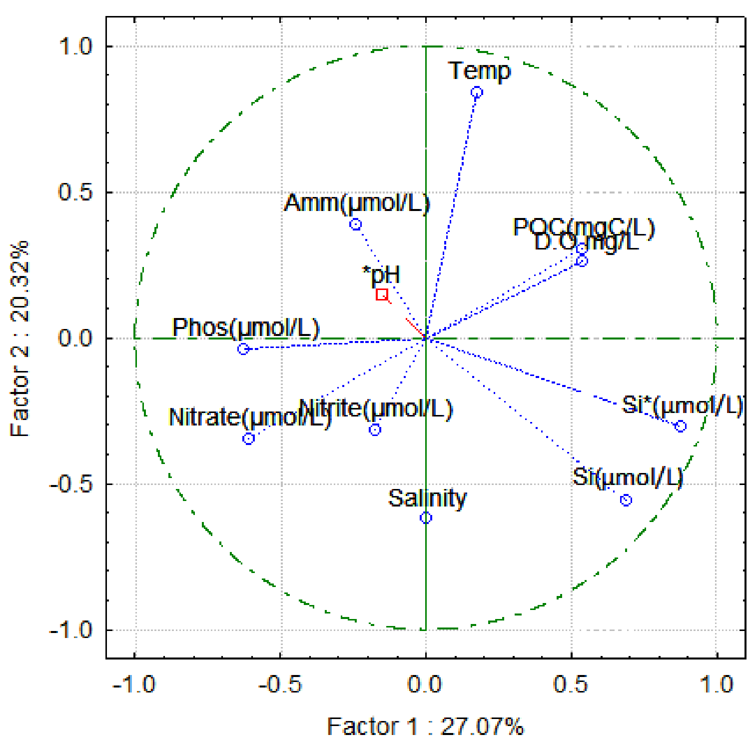


**Figure 3.** PCA analysis showing projection of variables on the factor-plane (1x2) with chlorophyll-a being the grouping variable.

**Table. 1** Factor axis 1x2 of variables with chlorophyll-a as the grouping variable

| Variable | Factor 1 | Factor 2 |
|---|---|---|
| **Salinity** | -0.004425 | -0.619442 |
| **Temp** | 0.172199 | 0.842886 |
| **Nitrate(µmol/)** | -0.613951 | -0.345378 |
| **Nitrite(µmol/)** | -0.179145 | -0.314980 |
| **Amm(µmol/)** | -0.244941 | 0.392273 |
| **Phos(µmol//L)** | -0.626469 | -0.037617 |
| **Si(µmol/L)** | 0.687051 | -0.554896 |
| **Si*(µmol/L)** | 0.875168 | -0.305875 |
| **POC(mgC/L)** | 0.532628 | 0.307775 |
| **DO mg/l** | 0.542712 | 0.260109 |

sufficient light and nutrients (including iron) are available, diatoms accumulate biomass with silicate and nitrate at a molar ratio of 1:1. In the deep near bottom layers of the ocean the dissolved Si concentration tends to increase more relative to that of nitrate, this being associated with the continued dissolution of skeletal opal, under high pressures (Kumar, 2006). Similarliy, Da' vila *et. al.* (2002) reported the influx of continental waters rich in dissolved silicate (DSi) and inherently poor in inorganic nitrogen (Perakis and Hedin, 2002; Huygens *et al*., 2008; Vargas *et al*., 2010). Whereas, Grasse *et al*. (2016) observed that waters on the shelf showed high Si $(OH)_4$ concentrations as a consequence of intense Si remineralization in the deep waters.

A cruise conducted by RV. Mtafiti within Kenyan waters observed dominant phytoplankton species to consist of diatoms *Chaetoceros* sp and *Rhizosolenia* sp (KMFRI, 2018). These ultimately add to the biotic particle flux to the bottom waters, while the Si pool is further enhanced by an annual terrigenous riverline sediment influx of around 7 million tonnes (Kitheka *et al.,* 2005).

The current study found the signature to be highly positively correlated to chlorophyll-a, the grouping variable along factor 1, employing the variable Si* as a proxy of upwelling (Fig. 3; Table 1). This indicates that upwelling is an important phenomenon driving productivity in the study area.

Seim and Gregg (1997) reported that topographic constrictions influence the basin circulation affecting the transport of dissolved nutrients between the basins separated by the topographic feature. The steep topographic elevation within Kenyan territorial waters as well as at the NKB could be influencing upward water movement/upwelling. Further, Jacobs *et al.* (2020), employing satellite imagery, documented high chlorophyll concentrations of up to 1 mg $m^{-3}$ over the NKB, associated with colder waters (25.8 °C), in comparison to the background values of ~0.5 mg $m^{-3}$ at ~26.5 °C in the surrounding waters. This is a clear cold productive signal, indicative of upwelling of cool, deep waters.

Further to the high Si* correlation, two other variables (POC and DO) were also significantly positively correlated to chlorophyll-a on the factor axis 2 (Fig. 3; Table 1), implying that POC remineralization also has some influence in the region's productivity. A novel study by Cavan *et al*. (2017) conducted the first ever observations of respiration rates (k) on slow-sinking particles, with k previously having only been measured on large, fast-sinking particles. Their study determined novel estimates of slow sinking POC turnover which were significantly higher (t ¼ 5.56) than the fast sinking particle turnover. They observed at least an order of magnitude difference in the rate at which the two fractions are turned over by microbes with 99 % of the carbon in the slow-sinking particles (POC) potentially being completely remineralized in less than a day. A similar level of degradation for fast-sinking particles took 36 days. The association of higher chlorophyll-a to high POC and DO concentrations can therefore be attributed to elevated microbial activity on POC boosted by high DO. The remineralized POC essentially releases nutrients to the ecosystem thus enhancing chlorophyll-a production.

The nitrate levels in the study area were negatively correlated in both factor axes, implying an inverse correlation to the productivity proxy chlorophyll-a. This may be due to the fact that the photic zone within the tropical region is not limited by light penetration and as such the nutrient consumption by phytoplankton is high, resulting in the water registering low nutrient levels (Omand and Mahadevan, 2015). Therefore, whereas the ocean productivity might be high, the nutrient content of the waters is low. It is also interesting to note that nitrate was highly negatively correlated (-0.6; see Table. 1) on factor axis 1 while corresponding to a high positive Si*correlation (0.87; see Table 1). The high Si* correlation to chlorophyll-a is indicative of high productivity. Si* is also associated with upwelling which is characterized by cool nutrient rich waters. Nutrients are essential for the occurrence of high productivity. The results of this study suggests high nutrient consumption as previously hypothesised, with low nutrient levels recorded in water samples, and an inverse correlation of nitrate to chlorophyll-a.

Figure 4 corroborates that chlorophyll-a was found to be directly proportional to Si* in this study. This is shown by the chlorophyll-a peak corresponding to the highest Si* values. Of interest is the high nitrate levels associated with high Si* levels. Upwelling is associated with the upward flow of cool nutrient rich waters, and since Si* is a proxy for upwelling, the above relationship might be indicative of nitrate also being associated with upwelled waters.

Figure 5 suggests that chlorophyll-a increases with decreasing phosphate levels, which is not the case, but could be a sign that high productivity puts a demand on phosphate, making it a limiting factor. A major part of primary production is considered to be supported by upwelling of deep waters rich in N and P. It is suggested that a limiting factor controlling primary production in the subtropical and tropical oceans is inorganic N and P (Falkowski, 1997; Capone *et al.*, 1997). The information in Table 1 further alludes to this in factor axis 1 where Si* was highly correlated to chlorophyll-a, while phosphate and nitrate were negatively correlated by similar values (-0.6). Since Si* is associated with upwelling and upwelling is associated with high productivity, the inverse relation of P and N, to chlorophyll-a could be due to their consumption by phytoplankton leading to depletion (Omand and Mahadevan, 2015).

High DO levels corresponded to high chlorophyll-a as observed in Fig. 6. According to Hirose and Kamiya

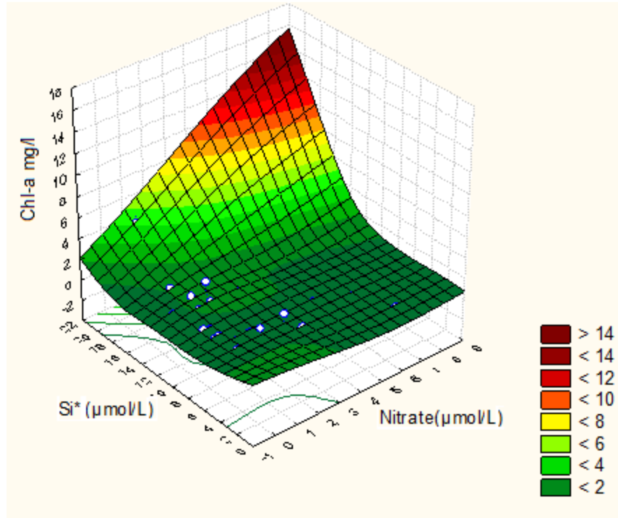


**Figure 4.** 3D surface plot of nitrate concentration (mmol/L) vs Si* concentration (mmol/L) vs chl-a concentration (mg/L): Z axis.

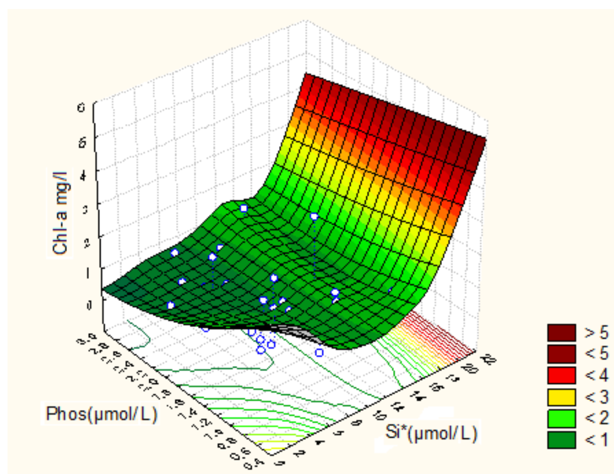


**Figure. 5.** 3D surface plot of Si* (mmol/L) vs Phos (mmol/L) vs Chl-a mg/L: Z axis.

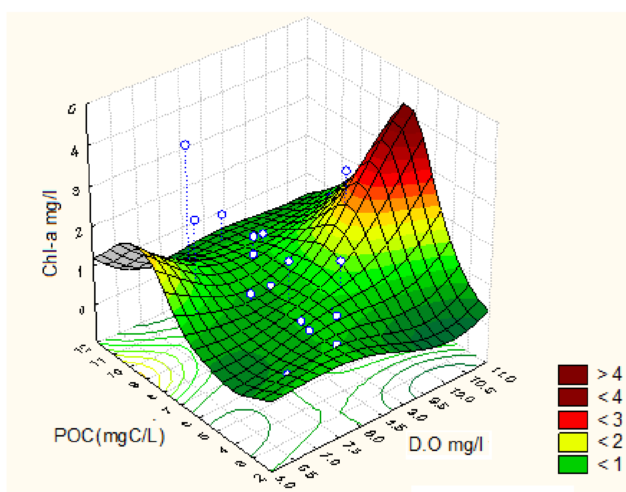


**Figure 6.** 3D surface plot of DO (mg/L) vs POC (mg C/L) vs Chl-a mg/L: Z axis.

(2003) abiotic and biotic factors have been known to influence productivity in about 90 % of the ocean surface. Further, as reported by Cavan *et al.* (2017) POC remineralization has been associated with microbial respiration, a process that in turn releases essential nutrients to the surrounding environment. Figure 6 illustrates chlorophyll-a as being boosted by high DO and POC levels, possibly due to the associated nutrient remineralization enhancing productivity. Azam *et al.* (1983) observed that higher temperatures with elevated microbial activity result in more efficient remineralization and leads to a lower export of POC to the abyss. Thus, lower latitude regions with low nutrient concentrations will contain a relatively active microbial loop that ensures remineralization and recycling before being exported from the euphotic zone (Azam *et al.*1983). This might explain the somewhat high direct relationship of temperature to chlorophyll-a (0.84); a further pointer to POC remineralization as observed by Azam *et al.* (1983).

This study aimed to obtain an understanding of the prevailing processes that might be driving the productivity of Kenyan territorial waters. Having employed PCA as a tool to associate the various oceanographic parameters and being cognizant of the underlining biogeochemical processes, it was possible to identify some of the abiotic and biotic factors as contributors to productivity. The analysis confirmed the fact that upwelling is a major contributor to the productivity of the study area. It was also evident that the system regenerates itself from the remineralization of POC which is further boosted by the high temperatures in the region.

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## References

Azam F, Fenche T, Field JG, Gra JS, Meyer-Rei LA, Thingstad F (1983) The ecological role of water-column microbes in the sea. Marine Ecology Progress Serie 10: 257-263

Broecker W S, Peng TH (1972) Tracers in the sea. Eldigio Press, Palisades, New York. 690 pp

Capone DG, Zehr JP, Paerl HW, Bergman B, Carpenter EJ (1997) *Trichodesmium*, a globally significant marine cyanobacterium. Science 276: 1221-1229

Cavan EL, Trimmer M, Shelley F, Sanders R (2017) Remineralization of particulate organic carbon in an ocean oxygen minimum zone. Nature Communications [doi: 10.1038/ncomms14847]

Da´ vila PM, Figueroa D, Muller E (2002) Fresh water input into the coastal ocean and its relation with the salinity distribution off austral Chile. Continental Shelf Research 22: 521-534

Falkowski PG (1997) Evolution of the nitrogen cycle and its influence on the biological sequestration of $CO_2$ in the ocean. Nature 387: 272-275

Fondo EN (2004) Assessment of the Kenyan marine fisheries from selected fishing areas. United Nations University Fisheries Training. Reykjavik, Iceland. 50 pp

Gallienne CP, Smythe-Wright D (2005) Epipelagic mesozooplankton dynamics around the Mascarene Plateau and Basin, Southwestern Indian Ocean. Philosophical Transactions of the Royal Society 363: 191-202

Grasse P, Ryabenko E, Ehlert C, Altabet MA, Frank M (2016) Martin Frank Silicon and nitrogen cycling in the upwelling area off Peru: A dual isotope approach. Limnology and Oceanography. 61: 1661-1676

Hirose K, Kamiya H (2003) Vertical nutrient distributions in the Western North Pacific Ocean: Simple model for estimating nutrient upwelling, export flux and consumption rates. Journal of Oceanography 59 (2):149-161 [doi: 10.1023/A:1025535003841]

Huygens D, Boeckx P, Templer P, Paulino L, Van Cleemput O, Oyarzu´n C, Muller C, Godoy R (2008) Mechanisms for retention of bioavailable nitrogen in volcanic rainforest soils. Nature Geoscience 1 (8): 543-548

Jacobs ZL, Jebri F, Raitsos DE, Popova E, Srokosz M, Painter SC, Nencioli F, Roberts M, Kamau J, Palmer M, Wihsgott J (2020) Shelf-break upwelling and productivity over the North Kenya Banks: The importance of large-scale ocean dynamics. Journal of Geophysical Research: Oceans 125 [e2019JC015519. https://doi.org/10.1029/2019JC015519]

Johnson DR, Nguli MM, Kimani EJ (1982) Response to annually reversing monsoon winds at the southern boundary of the Somali current. Deep-Sea Research 29: 1217-1227

Kabanova YG (1968) Primary production of the northern Indian Ocean. Oceanologica 8: 214-223

Kiilu BK, Kaunda-Arara, B, Oddenyo RM, Thoya P, Njiru JM (2019) Spatial distribution, seasonal abundance and exploitation status of shark species in Kenyan coastal waters, African Journal of Marine Science 41 (2): 191-201 [doi: 10.2989/1814232X.2019.1624614]

Kitheka JU, Obiero M, Nthenge P (2005) River discharge, sediment transport and exchange in the Tana

Estuary, Kenya. Estuarine Coastal and Shelf Science 63: 455-468

KMFRI (2018) The RV Mtafiti: Marine Research towards food security and economic Development for Kenya. Njiru JM, Ruwa RK, Kimani EN, Ong'anda HO, Okemwa GM, Osore MK (eds). Kenya Marine and Fisheries Research Institute, Mombasa, Kenya. 102 pp

Kumar DM (2006) Biogeochemistry of the North Indian Ocean. National Institute of Oceanography, Dona Paula, Goa. 25 pp

Lathuiliere C, Levy M, Echevin V (2010) Impact of eddy-driven vertical fluxes on phytoplankton abundance in the euphotic layer. Journal of Plankton Research 33 (3): 827-831

Le Manach F, Abunge CA, McClanahan TR and Pauly D (2015) Tentative reconstruction of Kenya's marine fisheries catch, 1950–2010. In: Le Manach F and Pauly D (eds) Fisheries catch reconstructions in the Western Indian Ocean, 1950-2010. Fisheries Centre, University of British Columbia. Fisheries Centre Research Reports 23 (2). pp 37-51 [ISSN 1198-6727]

Leetmaa A, Quadfasel DR, Wilson D (1982) Development of the flow field during the onset of the Somali Current, 1979. Journal of Physical Oceanography 12 (12): 1325-1342 [doi.org/10.1175/1520-0485(1982)012]

Liao X, Du Y, Zhan H, Wang T, Feng M (2017) Wintertime phytoplankton blooms in the western equatorial Indian Ocean associated with the Madden-Julian Oscillation. Journal of Geophysical Research: Oceans 122: 9855-9869 [doi.org/10.1002/2017JC013203]

Lutjeharms, J (1985) Location of frontal systems between Africa and Antarctica: some preliminary results. Deep-Sea Research 32: 1499-1509

Mahadevan A (2014) Eddy effects on biogeochemistry. Nature 506: 168-169

McClanahan TR (1988) Seasonality in East Africa's coastal waters. Marine Ecology Progress Series 44: 191-19

Miranda AA; Le Borgne YA, Bontempi G (2008) New routes from minimal approximation error to principal components. Springer. Neural Processing Letters 27: 197-207 [https://doi.org/10.1007/s11063-007-9069-2]

Molinari RL, Olson D, Reverdin G (1990) Surface current distributions in the tropical Indian Ocean derived from compilations of surface buoy trajectories. Journal of Geophysical Research 95 (5): 7217-7238 [doi.org/10.1029/JC095iC05p07217]

Munga CN (2013) Ecological and socio-economic assessment of Kenyan coastal fisheries: The case of Malindi-Ungwana Bay artisanal fisheries versus semi-industrial bottom trawling. PhD thesis, Gent University, Belgium. 210 pp

Nifong JC, Silliman B (2017) Abiotic factors influence the dynamics of marine habitat use by a highly mobile "freshwater" top predator. Hydrobiologia [doi 10.1007/s10750-017-3255-7]

Omand MM, Mahadevan A (2015) The shape of the oceanic nitracline. Biogeosciences 12: 3273-3287

Parsons TR, Maita Y, Lalli CM (1984) A manual of Chemical and biological methods for seawater analysis. Pergamon Press, Oxford, UK. 173 pp

Perakis SS, Hedin LO (2002) Nitrogen loss from unpolluted South American forests mainly via dissolved organic compounds. Nature 415: 416-419

Sarmiento JL, Gruber N, Brzezinski MA, Dunne JP (2004) High-latitude controls of thermocline nutrients and low latitude biological productivity. Nature 427: 56-60

Schott F, McCreary JP (2001) The monsoon circulation of the Indian Ocean. Progress in Oceanography 51: 1-123

Schott FA, Xie SP, McCreary JP (2009) Indian Ocean circulation and climate variability. Reviews of Geophysics 47 [doi: 10.1029/2007RG000245]

Seim HE, Gregg MC (1997) The importance of aspiration and channel curvature in producing strong vertical mixing over the sill. Journal of Geophysical Research 102: 3451-3472

Shenoi SSC, Saji PK, Almeida AM (1999) Near-surface circulation and kinetic energy in the tropical Indian Ocean derived from Lagrangian drifters. Journal of Marine Research 57 (6): 885-907 [doi.org/10.1357/002224099321514088]

Swallow JC, Molinari RL, Bruce JG, Brown O, Evans R (1983) Development of near-surface flow pattern and water mass distribution in the Somali Basin in response to the Southwest Monsoon of 1971. Journal of Physical Oceanography 13: 1398-1415

Swallow JC, Schott F, Fieux M (1991) Structure and transport of the East African Coastal Current. Journal of Geophysical Research 93: 245-570

Vargas CA, Martinez RA, San Martin V, Aguayo M, Silva N, Torres R (2011) Allochthonous subsidies of organic matter across a lake-river-fjord landscape in the Chilean Patagonia: implications for marine zooplankton in inner fjord areas. Continental Shelf Research 31 (3-4): 187-201

Weeks SJ, Shillington FA1(996) Phytoplankton pigment distribution and frontal structure in the subtropical convergence region south of Africa. Deep-Sea Research I43: 739-768

Zeller D, Harper S, Zylich K, Pauly D (2014) Synthesis of under-reported small-scale fisheries catch in Pacific-island waters. Coral Reefs *34* (1): 25-39 [doi: 10.1007/s00338–014–1219–1]

# Biophysical modelling of coastal upwelling variability and circulation along the Tanzanian and Kenyan coasts

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## Abstract

Ocean circulation, upwelling phenomena and chlorophyll-*a* concentrations were investigated within the framework of numerical model simulations with 1/12° nested horizontal grid-size, in the tropical western Indian Ocean, along the coasts of Tanzania and Kenya. Ekman driven upwelling exhibited high levels of spatial and temporal variability in the region, characterized by a more vigorous occurrence/intensification during the Northeast than the Southwest Monsoon season. A similar trend was observed for chlorophyll-*a* distribution, but with an additional strong contribution during the inter-monsoon period from March to April. Trend analysis of a SST-derived coastal upwelling index (CUI) computed over the Pemba Channel and offshore of the East African Coastal Current (EACC), for 24 years (1990 - 2013), revealed a general linear relation of the form CUI(yr) = $2.4 \times 10^{-7}$yr – 285, with a steady small annual increase of the upwelling phenomena by 0.0024/year ≃ 4% during the whole period of the simulation, which could be attributed to documented increasing trends of wind intensity and water volume transport in the region. The CUI exhibited the two most dominant peaks of variabilities on the range of annual and semi-annual timescales. The wind-stress southward component and the easting/westing veering of the northward EACC at 6°S revealed that these parameters were moderate and significantly correlated with the CUI ($r = -0.53$ and 0.52, $p<0.05$) respectively, further suggesting its intensification during the Northeast Monsoon season.

**Keywords:** Ekman pumping and suction, Wind stress curl, Upwelling and downwelling, Ocean models

## Introduction

Coastal upwelling events have been the subject of high interest among physical and biological oceanographers for many decades (Brink *et al*., 1983; Bakun, 1998; Durand *et al*., 1998; Capet *et al*., 2004; Echevin *et al*., 2005). Understandably, coastal upwellings are among the most productive marine eco-systems, providing food, sustaining fisheries and other economic and ecological services of great importance to human society (Cury and Roy, 1989; Bakun, 1998; Lett *et al*., 2007; Garcia-Reyes *et al*., 2015).

As a result of the on-going global concerns about climate change (Garcia-Reyes and Mahongo (this issue)) and associated perturbations on the patterns of general atmospheric and oceanic circulations, many scientific studies have directed their attention towards understanding how such changes may impact the strength/ intensity of upwelling systems around the world (Garcia-Reyes *et al*., 2015). Only recently have these concerns been raised in the western Indian Ocean and awareness among the marine scientific community and relevant stakeholders has been raised (Roberts, 2015).

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Along the coasts of Tanzania and Kenya the development of a near-shore negative wind-stress curl, and consequent positive Ekman vertical velocities (i.e. Ekman suction) during the Northeast Monsoon as observed by Collins *et al.* (2012) and Manyilizu *et al.* (2016), suggest the occurrence of an active upwelling phenomenon. The opposite is also observed during the Southwest Monsoon (Collins *et al.*, 2012), leading to a downwelling phenomenon (i.e. Ekman pumping). Coastal upwelling along the Tanzanian and Kenyan continental shelves can be visually diagnosed from thermal expressions of high resolution sea surface temperature (SST) products (able to resolve detailed patterns of spatial and temporal scale variabilities, for example fronts, (SST gradients), and filaments as depicted in Fig. 1) simulated by the Regional Ocean Modelling Systems (ROMS) with a horizontal grid-resolution of 1/12°, for the 2nd January of year 8. In Fig. 1, the super-imposed vectors indicate the direction of the flow field (circulation). The snapshot portrays a typical situation prevalent in the region, characterized by the presence of the warmer EACC, that permanently propagates northward along the Tanzanian and Kenyan coasts (Swallow *et al.*, 1991; Nyandwi, 2013). The EACC receives most of its water supply from the warmer South Equatorial Current (SEC), after its splitting on arrival at the African coast near 12°S (Swallow *et al.*, 1991; Schott *et al.*, 1988, 2009; Manyilizu *et al.*, 2016). Upon receiving such supply, the EACC becomes a well-defined and distinct structure along the coasts of Tanzania and Kenya between 11°S and 3°S, and it carries about 19.9 Sv (1 Sv = $10^6$ $m^3s^{-1}$) of the volume transport in the upper 300 m of the water column, across a zonal distance of 120 km offshore (Swallow *et al.*, 1991). Its main core lies at the offshore side of the chain of islands formed by Mafia, and Unguja and Pemba (Zanzibar archipelago), whereby parts of the flow upslopes onto the narrow continental shelf and recirculates around the islands, as documented by Mahongo and Shaghude (2014), Roberts (2015), and Mayorga-Adame *et al.* (2016).

The major gateway for the upsloping flow appears to be located between Unguja and Pemba Islands, as observed and captured by the hydrographic measurements presented by Nyandwi (2013), Roberts (2015) and the modelling study by Mahongo and Shaghude (2014). For details of the main current systems in the western Indian Ocean (WIO), the reader is referred to the works by Schott *et al.* (2009), especially the model data comparison section (see Fig. 2).

A paucity of hydrographic data in this region exists with few dedicated studies to investigate the nature and characteristics of the East African upwelling events along the coasts of Tanzania and Kenya even though these localized upwelling events help to service the need (subsistence) of the local coastal communities which heavily depend on artisanal fishing (Mapunda,1983; Ministry of Agriculture Livestock and Fisheries, 2016). It is only recently that regional initiatives to study these upwelling events in the WIO region along these coasts have emerged, within the framework of the second International Indian Ocean Expedition (IIOE-2), through the Western Indian Ocean Upwelling Research Initiative (WIOURI) project (Roberts, 2015), and the Productivity of the East African Coastal Current (PEACC) project (between 2016-2018), endorsed by the IIOE-2, and supported through a MASMA grant from the Western Indian Ocean Marine Science Association (WIOMSA) (https : //www.wiomsa.org/ongoing – project/), from which the present study is derived.

Disturbing environmental climate change patterns have been recently diagnosed in the WIO equatorial region, reflected in the form of (1) excessive unprecedented sea-surface warming (Roxy *et al.*, 2014), and (2) increasing trends and intensification of the wind system and oceanic surface currents, and their kinetic energy (Mahongo *et al.*, 2012; Backeberg *et al.*, 2012). In this study it is therefore aimed to investigate the nature, spatial and temporal variabilities of the coastal upwelling events along the coasts of Tanzania and Kenya. The main research question is ‘how do the upwelling events along the coasts of Tanzania and Kenya relate to the on-going changes of patterns in atmospheric and oceanic circulations, as documented by Mahongo *et al.*, 2012 and Garcia-Reyes *et al.* [this issue].

To achieve the goal/objectives of this study, a SST’s coastal upwelling index (CUI) from a high-resolution hydrodynamic model output was computed and investigated. Furthermore, the CUI variability against atmospheric winds was inspected, together with the structure of the EACC, translated in terms of its zonal and meridional velocity components.

## Material and methods

### Physical model

ROMS is a split-explicit free-surface ocean circulation model designed especially for accurate simulation of regional oceanic systems and coastal margins, using higher-order numerical schemes (Shchepetkin and McWilliams, 2005). The model solves the discrete set of primitive equations of motion in a staggered C-grid, under an earth rotating reference frame using the hydrostatic and Boussinesq approximations. For details of the model kernel, it is recommended that the reader consult the paper by Shchepetkin and McWilliams (2005).

### Biophysical model

The biophysical model used in this study is the medium complex level biogeochemistry NPZD model (Gruber *et al.*, 2006). It simulates the simple interaction of four ecosystem properties, namely, nutrients (N), phytoplankton (P), zooplankton (Z) and detritus (D) (Fasham *et al.*, 1990). To ensure a more realistic solution within the region of interest, the closing terms for phytoplankton and zooplankton used were derived from higher-order numerics instead of the usual linear schemes. For details of the model it is recommended that the reader consult the work of Fasham *et al.* (1990).

### Modelling strategy

The model configuration was built using ROMSTOOLS (Penven *et al.*, 2008). It consists of two-level rectangular grids, connected via a two-way nesting approach (Debreu *et al.*, 2012). The outer domain ("parent model") spans from 35°E to 90°E, and 30°S to 30°N, which essentially covers the whole WIO, with a horizontal grid resolution of 1/4°, nearly 25 km. The inner domain ("child model", 38.5°E – 42°E, 10°S – 4°S) was set to cover the whole excursion of the EACC, and it runs with a horizontal grid resolution of 1/12°, about 8 km. On the vertical the configuration has been set with 60 vertical σ-layers, and the grid controlling parameters at sea-floor was $\theta_b$=0, at sea-surface $\theta_s$=6, and the layers thickness $h_c$=10.

Two different experiments were performed. The first was driven by climatological surface forcing and lateral open boundary conditions. It used monthly averages surface fields, which includes the wind-stress, fresh-water fluxes, heat-flux and salt-flux, gridded at 1/2°×1/2° derived from COADS05 (Da Silva *et al.*, 1994). To boost the air-sea interaction over the COADS05 product, the surface heat-flux was augmented using a 9-km satellite derived SST (pathfinder product), as a restoring term for the boundary layer processes with a timescale of about 60 days (Colas *et al.*, 2012). To augment COADS05 wind-stress (important for accurate representation of coastal dynamics), winds derived from QuikScat satellite Scatterometer Climatology of Ocean Winds (SCOW) from (1999 - 2009), gridded at 1/4°×1/4° by Risien and Chelton (2008) was used. This augmentation boosts the low resolution COADS product. For further details on boosting of the model surface forcing, consult the work by Colas *et al.* (2012). SCOW is known to capture small-scale features that are dynamically important to both the ocean and the atmosphere (e.g. SST gradient), but are not resolved in other observationally-based wind atlases or in NCEP-NCAR re-analysis fields (Risien and Chelton, 2008). The lateral open boundary fields were derived from hydrographic datasets from the World Ocean Atlas 2009 (WOA09, Conkright *et al.*, 2002), gridded monthly climatology at 1° (Conkright *et al.*, 2002). The flow field was derived from Ekman and geostrophic equations, the latter computed from hydrography, with the reference depth for integration set to 1000 m below the sea surface.

The second experiment was configured to account for the inter-annual variabilities. It was forced at sea-surface by wind-stress derived from the ERA Interim re-analysis product, interpolated online onto the grid, using the bulk formulation, while employing the relative-wind approach, to ensure realistic representation of kinematic energies. The lateral open boundary conditions were derived from GLORYS global re-analysis (https://www.mercator-ocean.fr/sciences-publications/glorys/). The simulations were carried out over the period spanning 1990 to 2013 with 3 years of adjustment.

The biogeochemical model was coupled to the climatology physical model through the advection-diffusion equation, whereby the state variables of the NPZD model holds a separate equation which describes its motion in time and space (Peter, 2002). The monthly climatologies for nitrate, phosphate, silicate and oxygen concentrations for the lateral open boundaries were derived from CARS2009 dataset (Ridgway *et al.*, 2002). SeaWifs was used to obtain a climatology of surface chlorophyll-a concentration (WOA, 2001, Conkright *et al.*, 2002). Freshwater river runoff was derived from the global climatology dataset of Dai *et al.* (2009).

### CNES-CLS13 data

The large-scale oceanic surface geostrophic circulation in the region was derived from the mean dynamic topography product (CNES-CLS-13, https: //www.aviso.altimetry.fr/en//data/products/auxiliary-products/references.html). The product is computed from long-term (1993-2012) in-situ oceanographic datasets, including drifter velocities, hydrological profiles for the upper 350 m below the sea-surface, mapped within a grid box-size of 1/4°× 1/4°. It also includes remotely sensed altimetry measurements and outputs from numerical models. The computation uses advanced processing techniques, based on multivariate objective analysis. The product is known to capture oceanographic features with relatively short scale structures, leading to better representation of the flow field when compared against previous global mean dynamic topography products (Rio and Hernandez, 2004; Rio *et al.*, 2011).

### Tide-gauge data

The sea-level data used to evaluate the model performance was downloaded from the Joint Achieve for Sea-Level (http://uhslc.soest.hawaii.edu/), retrieved from a single tide-gauge station deployed at reference station 151A located at the coastal island of Zanzibar, at 39.19°E, 6.15°S. While the data are provided from the source as hourly values or more frequent intervals of about 15 minutes, which are then reduced to hourly intervals, a daily time-scale from 1984 to 2018 has been used in this study. The data is calibrated, quality controlled, and made available for research purposes in a standardized format (Caldwell *et al.*, 2015).

### Satellite ocean colour data

To evaluate the performance of the biological component of the model, the simulated chlorophyll-a concentration against monthly mean climatology maps of sea surface chlorophyll-a concentration derived from the satellite based optical sensors MODIS-AQUA was compared. MODIS is a Moderate Resolution Imaging Spectroradiometer instrument onboard a NASA satellite (https://oceancolor.gsfc.nasa.gov). MODIS data is available from July 2002 to the present. The product used here, termed GMIS-MODIS-AQUA was extracted from the European Union Data Portal (https://data.europa.eu/data/dataset), made freely available by the European Commission Joint Research Centre. The product is gridded globally, in a logarithmic scale over a mesh of 9 km grid size. The temporal coverage ranges between 4 July 2002 and 25 January 2018.

### Data Analysis and techniques

Matrix Laboratory software (MatLab, https://www.mathworks.com/) was used for the data processing, computation, and visualization. Several techniques have been implemented to extract necessary information from the datasets used in the present study. Some of these techniques were: (1) Geostrophic balance, which is a regime attained from the horizontal components of the momentum equation, when the pressure gradient force is balanced by the Coriolis force, due to the rotation of the earth. From these the geostrophic velocities of the circulation are computed as follows:

$$u = -\frac{g}{f}.\frac{\partial \eta}{\partial y} \text{ and } v = \frac{g}{f}.\frac{\partial \eta}{\partial x} \tag{1}$$

Here $g$ and $f = 2\pi\Omega.\sin(\theta)$ represent the acceleration due to gravity and the Coriolis parameter respectively. $\Omega = \frac{2\pi}{T}$ is the frequency of the earth's rotation, with period $T$ of about 24 hours, and θ is the latitudinal position; (2) In addition, the Multi-Tapper Method was used to compute the power-spectral density of the EACC volume transport, and the wavelet spectral analysis was applied on the CUI time series. Important references for these techniques can be found in Thomson (1982) and Smith-Boughner and Constable (2012). Freely available Toolkits for various computer operative systems can be accessed at (https://dept.atmos.ucla.edu/tcd/multi-taper-method-mtm); (3) Simple linear regression analysis was performed to inspect the trends in the CUI time series, and the Pearson's correlation coefficients were determined between CUI and geophysical parameters such as wind-stress and current velocity. Spatial distribution of areas of upwelling were mapped using Ekman suction, using the equation below:

$$U = \frac{\tau}{\rho o f L u} \tag{2}$$

Where τ is the alongshore windstress, ρo - is the mean seawater density, f - is the Coriolis parameter (already defined earlier). Lu - is the cross-shore horizontal scale. Temporal variability of the CUI was determined based on thermal expressions of SST, following the method developed by Demarcq and Faure (2000), and adapted by Ramanantsoa *et al.* (2018) for the southern Madagascar upwelling, defined by the following equation:

$$CUI = \frac{SSToffshore - SSTinshore}{SSToffshore - SSTmean} \tag{3}$$

Where SSToffshore and SSTinshore are the computed SST average within the offshore and inshore boxes respectively shown in Fig. 1. SSTmean is the mean between the average SSToffshore and SSTinshore.

It is important to mention that the terms used in this study to qualify the statistics (i.e. the strength of the correlation coefficients and coefficients of determination) are based on the criteria adopted in the paper by Assuero *et al.* (2006).

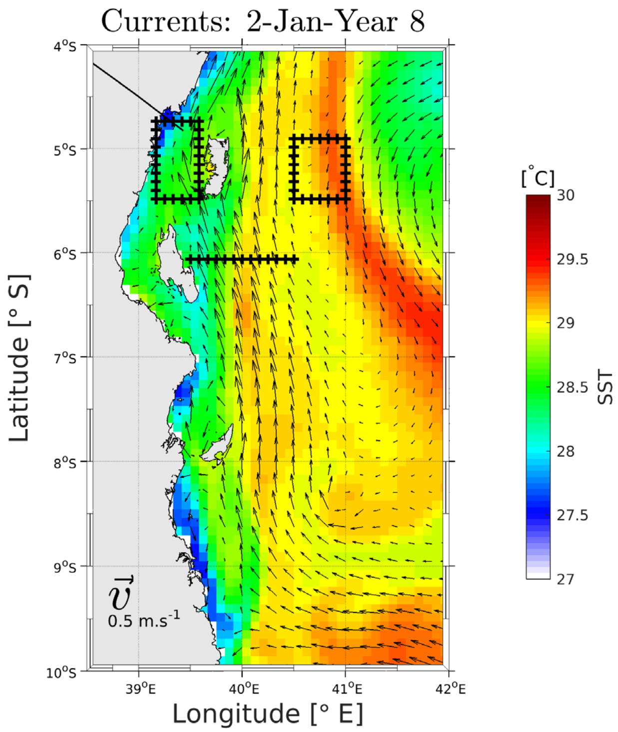


**Figure 1.** Model simulation of the instantaneous view of the flow field illustrating important synoptic features of the circulation (arrows), and spatial variations of the sea surface temperature (colour shading) along the coasts of Tanzania and Kenya. Output from the nested model with a horizontal grid resolution of 1/12°, for the 2nd January Year 8. The arrows indicate the flow direction. Note the boxes to the west (inshore) and to the east (offshore) of the northernmost island (Pemba), used to compute the SST upwelling index. Note also the transect at 6°S between the middle island and offshore, across the EACC, used to compute the time-series of the volume transport of the EACC shown in Figure 3. The plain line in the upper left corner of the figure, over the continent, represents the geographical border between Tanzania and Kenya.

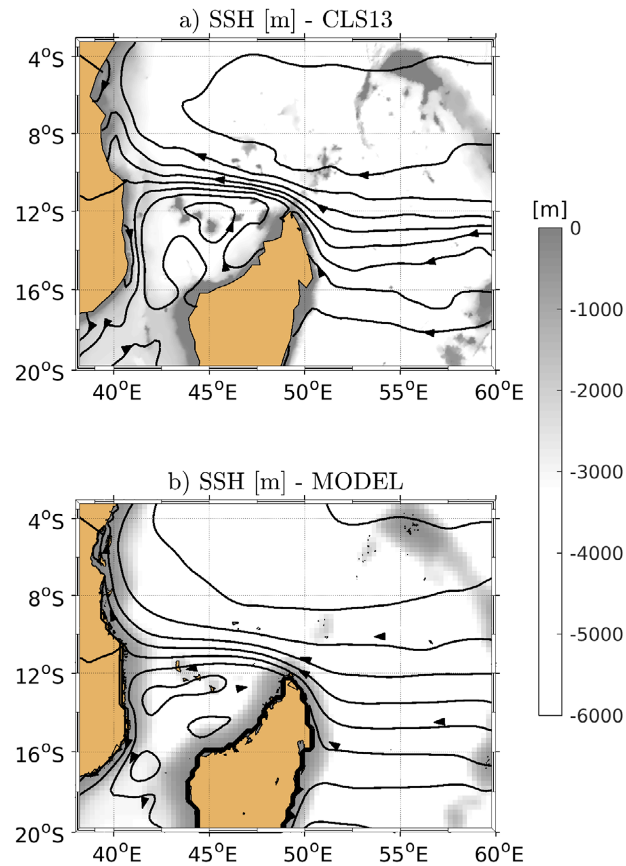


**Figure 2.** Model and data comparison for the large-scale oceanic geostrophic circulation, computed from variations of the sea-surface. a) Streamlines of mean dynamic topography from CLS-CNES13, and b) model simulated mean sea-surface height. Contour interval 0.05 m, and the arrows indicate the direction of the currents. Note that it reflects the circulation patterns well. Background shading shows the sea-floor topography.

## Model performance

The ability of ROMS to accurately simulate the flow field in the region of interest has been demonstrated successfully in previous studies (Manyilizu *et al.*, 2014, 2016; Gamoio *et al.*, 2017), including Manyilizu *et al.* [this issue].

### Large-scale circulation

To corroborate this fact, Fig. 2 shows the sea surface height (SSH) streamlines from both observations (Fig. 2a) and the result from the climatological model simulation (Fig. 2b), illustrating the upper ocean large-scale geostrophic circulation derived from variation of the sea-surface ($\zeta$), expressed by the velocity components *(u)* and *(v)* with relation to *(x)* and *(y)* direction respectively (Equation 1).

Fig. 2a was constructed using the CNES-CLS-13 mean dynamic topography, and Fig. 2b, model climatology of sea-surface height. The contour interval is 0.05 m, the stream-arrows indicate the direction of the ocean currents, and the background shading is the seafloor topography. The model resembles the observed patterns well, characterized by the presence of the main oceanographic features of the circulation documented in many publications (Manyilizu *et al.*, 2014; Schott *et al.*, 2009). For example, a good representation of the split of the South Equatorial Current (SEC) at northeast coast of Madagascar between 16 - 17°S (Fig. 2b) is clearly seen. The impact of the mesoscale eddies in the general circulation patterns within the Mozambique Channel (as indicated by the clockwise and anticlockwise features, denoting cyclonic and anticyclonic eddies) is also clearly seen. The splitting of the western extension of the North East Madagascar Current (NEMC) at about 12°S near the African mainland into two opposing branches is also evident. The northward branch feeds the EACC along the coast of Tanzania and Kenya. The model is also able to reproduce the cross-equatorial cell, portrayed by the clockwise cyclonic recirculation to the north of Madagascar, at the northern sector of the South Equatorial Current (SEC). This cross-equatorial cell ranges between 5 - 10°S, and is driven by Ekman pumping, in response to wind forcing at the northern boundary of the south-easterlies (Schott *et al.*, 2009).

In spite of the model's ability to mimic observations well, there are also some discrepancies between them. For example, the stream-lines at the eastern boundary of the domain presented in Fig. 2 shows relatively larger spacing between the contours in the model (Fig. 2b) than in the observation (Fig. 2a). This indicates that the SEC in the model is weaker than in the observation. The reader may find it informative to compare these details (Fig. 2) with the description presented by Schott *et al.* (2009).

## EACC volume transport at 6°S

To assess the ability of the model to reproduce the structure of the EACC through the water column, the volume transport of the EACC in the upper 500 m of the water column at 6°S, across the width of the current between 39.5 and 40.5°E, has been computed (Fig. 3). For reference, see the transect position in Fig. 1, which seems to capture the full structure of the current's main core. The model shows high level of transport variability, minimum and maximum fluctuations ranging between 5 and 28 Sv, observed in 1990 and 1999 respectively (Fig. 3a). The power-spectrum presented in Fig. 3b suggests dominant modes of variability (i.e. power-density which is equal or above 1 $Sv^2$ $year^{-1}$) ranging from intra-seasonal to inter-annual and longer time-scales (i.e. 3 - 5 years' cycle, 1 and 2 cycles $year^{-1}$ in Fig. 3b). This is consistent with the literature which indicates that these modes of variability are strongly coupled by marked seasonality (Schott *et al.*, 2009; Manyilizu *et al.*, 2016). The quantified annual mean was 16.2 Sv and the standard deviation was 3 Sv. Using direct hydrographic observations, Swallow *et al.* (1991) has given an estimate of 19.9 Sv. Therefore, the model results from this study show good agreement with observed data.

## Sea level in Zanzibar

In order to inspect the performance of the inter-annual model experiment, the time-series variations of the sea-surface height, and its corresponding power-spectra for the entire model period, spanning from 1990 to 2013, were computed to compare against the long-term observation of sea-level from 1984 to 2018. This dataset represents the only observational data available, collected in Zanzibar by the University of Hawaii Sea-level Center (UHSLC), using a tide-gauge located at 39.19°E, 6.15°S.

As can be seen from the results presented in Fig. 4, both the model and observations show similar general patterns characterized by a consistent decreasing profile of the sea-level height prior to the year 2000, and an increasing profile after 2000. Furthermore, both products (model and observation) also capture the peak of sea-level height that occurred between 1997 and 1998, likely associated with one of the most intense historical ENSO event that severely devastated the WIO region (Schott *et al.*, 2009). Good agreement between both products is present for the maximum levels amplitude range (Fig. 4). However, the model (Fig. 4b) appears to exaggerate the reproduction of

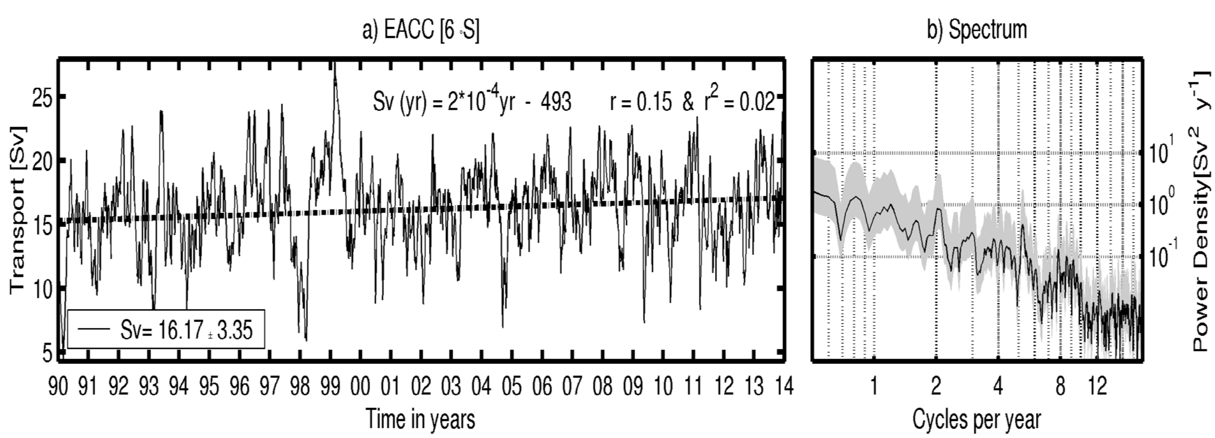


**Figure 3.** Model derived time-series of the volume transport (Sv) of the EACC, vertically integrated in the upper 500 m below the sea surface (a), and its b) power-spectrum ($Sv^2$ $year^{-1}$) estimated using the multi-taper method, computed at 6°S, across the width of the current between 39.5 and 40.5°E. The dashed-line represents the linear trend following the equation Sv (yr) = $2x10^{-4}yr - 493$, with correlation coefficient (r), and coefficient of determination ($r^2$). The grey envelope highlights the standard deviations around the mean signal (black line).

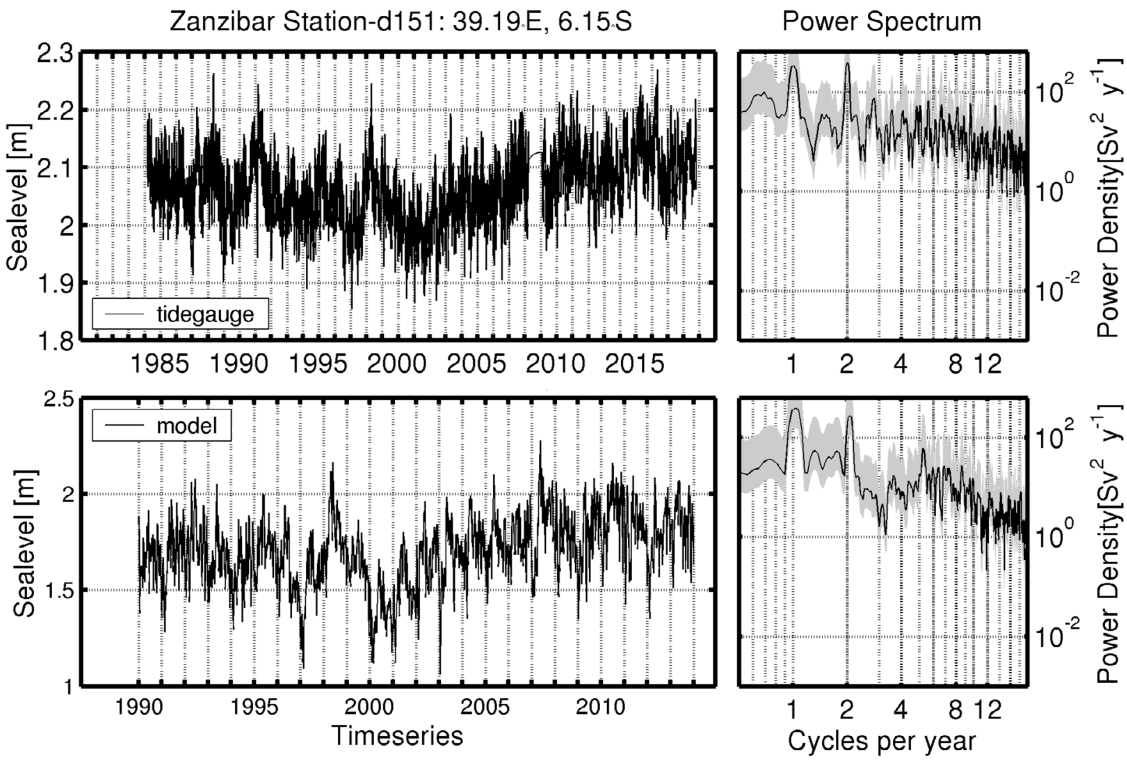


**Figure 4.** Data (upper panel) and Model (lower panel) comparison for the sea-level variation (m) at a tide-gauge mooring site located in Zanzibar. The observed data has been extracted from University of Hawaii Sea-level Center, and spans from 1984 to 2018. The model time-series spans from 1990 to 2013. The left panels show the inter-annual variations, and the right panels show their corresponding power-spectra ($Sv^2$ $year^{-1}$) computed using the multi-taper approach. The grey envelope highlights the standard deviations around the mean signal (black line).

lower bound amplitudes of the signals, where its minimum reached nearly 1 m. On the other hand, the observational data has barely reached a minimum amplitude of 1.85 m (Fig. 4a). It is not surprising as the model sea surface height (SSH) used here is an absolute parameter (i.e. the changes in SSH is with respect to a fixed absolute reference frame, e.g. earth's center). Additionally, the sea-level as observed by the tide-gauge is a relative (i.e. is measured locally relative to the land), and is thus the sum of absolute sea level changes and vertical motions of the land, heavily impacted by geological activities. Nevertheless, in spite of such apparent discrepancies, it is remarkable to note that both products have reproduced identical power-spectra profiles across the whole scales of variabilities. The strongest signals were distinctly characterized by both annual and semi- annual frequencies, identified by peaks of one cycle per year and two cycles per year, respectively. It is likely that these predominant peaks are related to the seasonal reversal of the monsoons, which creates two seasons. Furthermore, both products also reproduce vigorous inter-annual (frequency < 1 cycle $year^{-1}$) and intra-seasonal events (frequency > 8 cycles $year^{-1}$), with a consistent decreasing slope towards lower energy levels. There is also a relatively strong variability at frequency of 4 - 5 cycles $year^{-1}$, which could possibly suggest mesoscale activity identified by Gamoio *et al.* (2017).

## Chlorophyll-*a*

The observed and modelled monthly climatology of sea surface chlorophyll-*a* concentrations are presented in Fig. 5 and Fig. 6 respectively. Both model and observations reveal that higher chlorophyll-*a* concentrations are generally confined closer to the coast (presumably over the narrow continental shelf), and lower concentrations are located slightly offshore, throughout the annual cycle (i.e. January to December). Both products also suggest that the lowest concentration of chlorophyll-*a* in the whole domain scale occurs in January. It is not clear why such a pattern is presented, as it stands in stark contrast with the distribution in the preceding month and the month thereafter (i.e. December and February). While both the model and observations show consistently comparable spatial and temporal patterns for relatively higher levels of chlorophyll-*a* concentration, it is also noticeable that the model has struggled to reproduce lower levels in

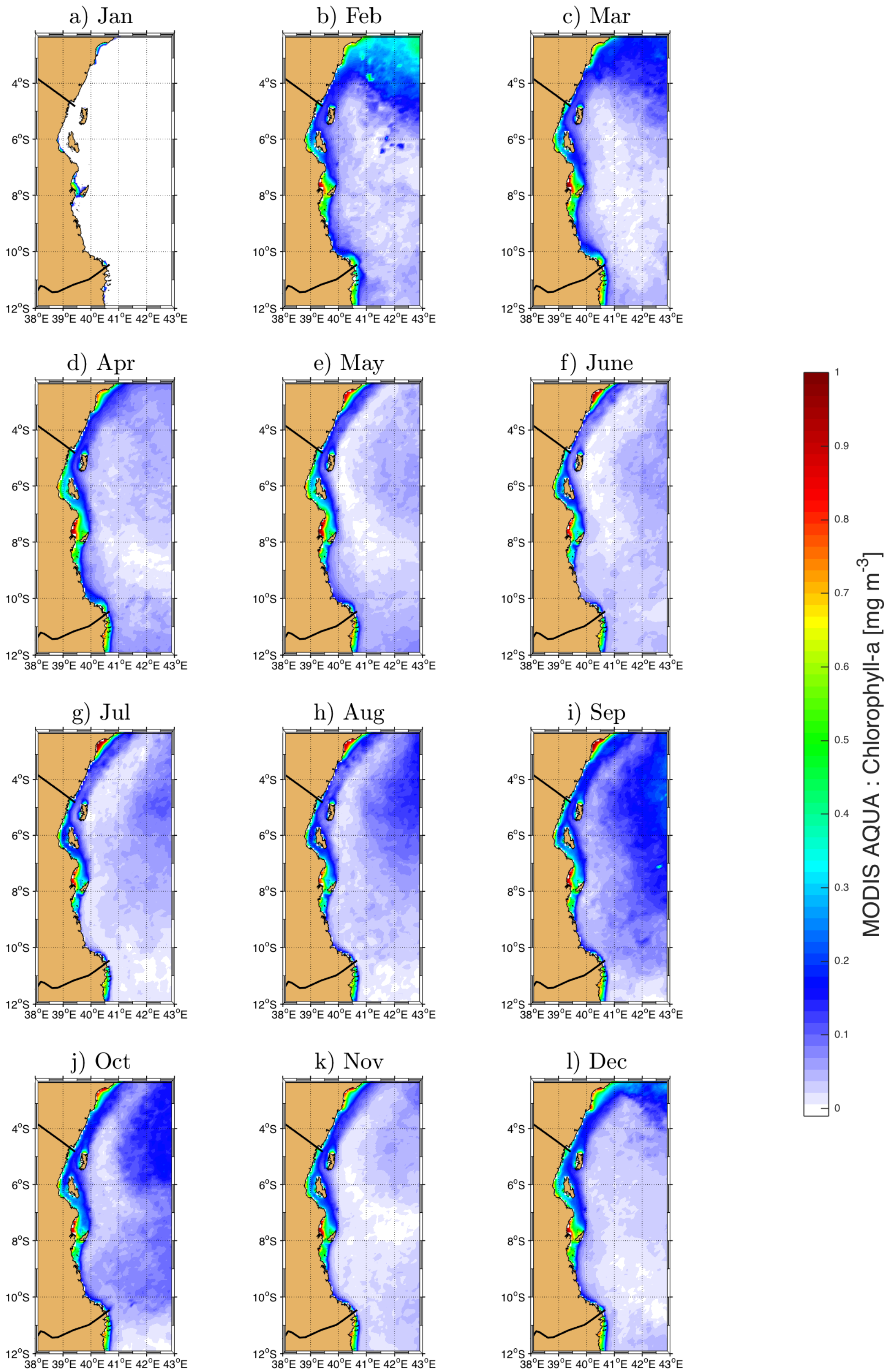


**Figure 5.** Surface maps of the MODIS-AQUA satellite-derived monthly climatologies of the estimated chlorophyll-*a* concentrations (mg m$^{-3}$) throughout the annual cycle along the coasts of Tanzania and Kenya.

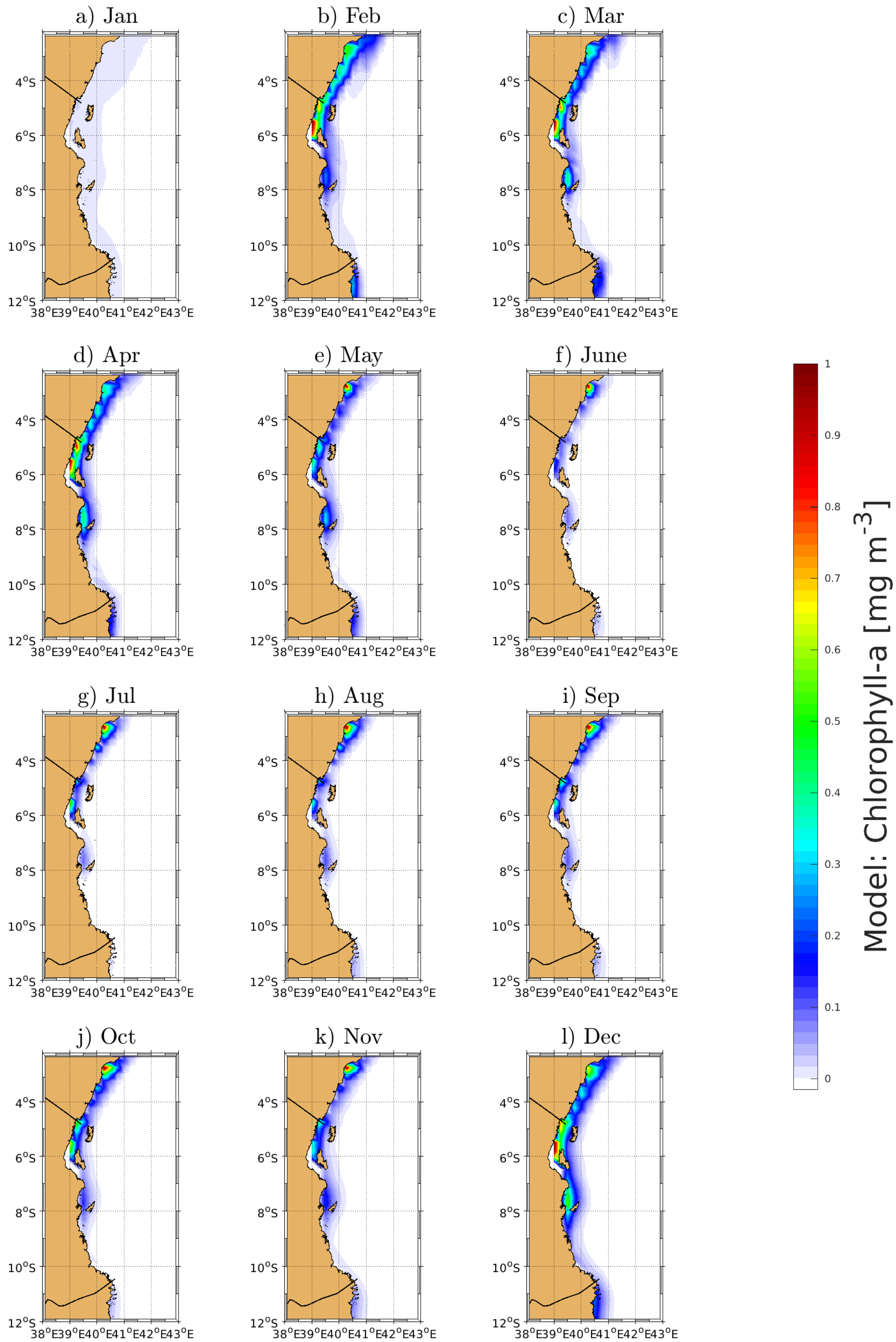


**Figure 6.** Surface maps of the model-derived monthly climatologies of the estimated chlorophyll-*a* concentrations (mg m$^{-3}$) throughout the annual cycle along the coasts of Tanzania and Kenya. Notice that at specific locations within the Zanzibar Channel the model grid resolution struggled to reproduce chlorophyll-*a* concentrations. This could correspond to shallower areas in the channel.

chlorophyll-*a* concentrations in the offshore environment. Nevertheless, the model appears to reproduce the biological property investigated reasonably well.

Fig. 6 will be revisited in the results section and discussed in light of the model derived surface maps of the Ekman upwelling index.

## 4. Results and Discussion

### Spatial and temporal variation of the model derived Ekman upwelling

To investigate the nature and characteristics (i.e. spatial and temporal variabilities) of the upwelling events along the Tanzanian and Kenyan coasts, the surface spatial expressions of the upwelling phenomenon were computed and mapped, calculated through estimates of the Ekman vertical velocities (Ekman pumping and suction), derived from the meridional wind-stress vector ($\tau$), scaled by the cross-shore horizontal length scale of the upwelling Lu (width of Ekman divergence), following the formula derived by Bakun (1973), as presented in Marchesiello and Estrade (2010) (see Equation 2).

It is important to mention that the horizontal grid resolution has been used in the equation instead of the commonly used Rossby radius of deformation, which in the region of interest ranges between about 100 km in the south and 230 km in the north (Chelton *et al.*, 1998). The use of finer grid resolution has been suggested (Capet *et al.*, 2004), because it has been diagnosed that the Rossby radius usually over-estimates the magnitude of the upwelling rate (Capet *et al.*, 2004; Marchesiello and Estrade, 2010). In Equation 2, a positive (negative) U denotes an Ekman suction (pumping), indicative of upwelling and downwelling events respectively. Fig. 7 shows the results (monthly climatologies) throughout the year cycle. It suggests that upwelling events along the coasts of Tanzania and Kenya are highly variable, but a normal occurrence.

Throughout the annual cycle it is apparent that stronger upwelling events (Ekman suction) occur on-shore almost along the whole coastal zone, and offshore downwelling (Ekman pumping; more to the north of 6°S than in the south) is persistent from December to February (Fig. 7a,b,l). It is important to mention that this is the period dominated by the Northeast Monsoon winds. During this period an exception is observed in a narrow zonal strip that extends between northern Pemba Island and the African mainland, lying exactly at the border between Tanzania and Kenya, where a downwelling event (Ekman pumping) is persistent. During the dominant on-shore downwelling period along the coast observed mostly from July to October (Fig. 7g and 7j), this zonal band switches to a persistent upwelling dominated region. It is also important to mention that the period spanning from July to October is characterized by the Southwest Monsoon winds. During the month of June (Fig. 7f), upwelling is more prevalent both on-shore and offshore, except at a locality (3 - 4.5°S) to the south of Kenya.

The results presented here clearly indicate the dominant occurrence of coastal upwelling during the Northeast Monsoon and downwelling during the Southwest Monsoon, which suggests a seasonal dependence. Nevertheless, the occurrence of isolated small patches of upwelling events during the Southeast Monsoon, and downwelling during the Northeast Monsoon may suggest that not all observed coastal upwelling events present in Fig. 7 are driven by the same physical process, such as wind-stress curl.

### Spatial and temporal variation of the model derived chlorophyll-a

To determine the biological response in the upwelling area, the model- derived surface monthly climatologies of chlorophyll-a concentrations was again inspected. As previously indicated, Fig. 6 shows spatial and temporal distribution during a full annual cycle. As with the upwelling events (Fig. 7), it is notable that chlorophyll-*a* also shows high levels of spatial and temporal variabilities along the Tanzanian and Kenyan coasts. The model suggests higher concentrations along the coast in December (Fig. 6l), and from February to April (Fig. 6b to 6d). On the other hand, lower concentrations are more notable in January (Fig. 6a), and from June to September (Fig. 6f to 6i) respectively. It is evident that there are higher concentrations of chlorophyll-*a* during the inter-monsoon period from the Northeast Monsoon to the Southwest (March - April) than that from Southwest to Northeast (October - November).

One should note that higher surface chlorophyll-a distribution presented in Fig. 6 does not necessarily co-occur with the higher distribution patterns of upwelling events as suggested in Fig. 7. Their confinement to the coast could suggest potential contribution of land-based material flushed into the sea by the rivers and streams. This may lead to the conclusion that the biological responses observed in the region could be a consequence of both upwelling events and river discharges.

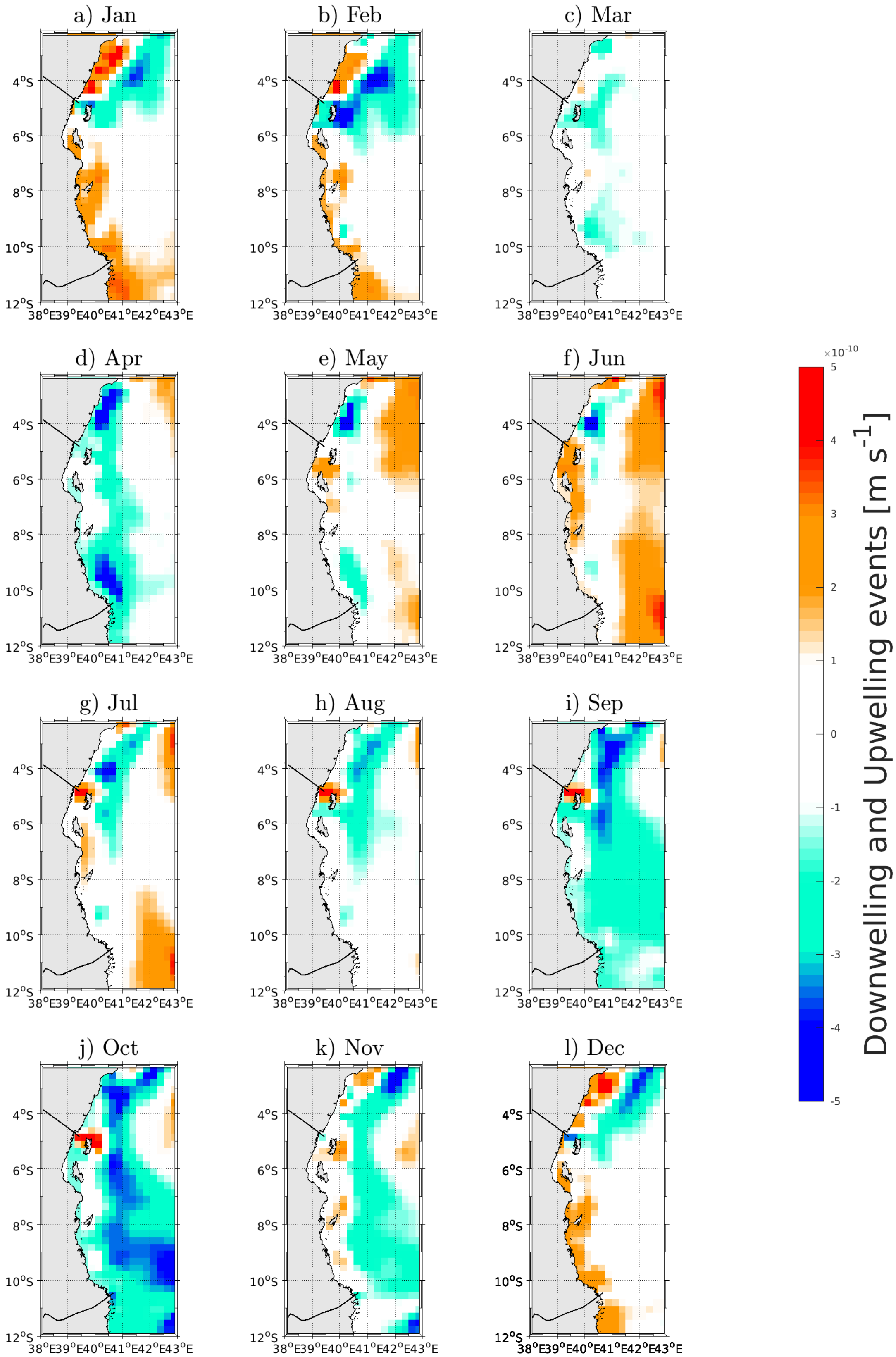


**Figure 7.** Surface maps of the model-derived monthly climatologies of the upwelling and downwelling velocities (m s$^{-1}$) estimated using Equation 2. Positive (negative) are indicative of upwelling (downwelling) events respectively, along the coasts of Tanzania and Kenya.

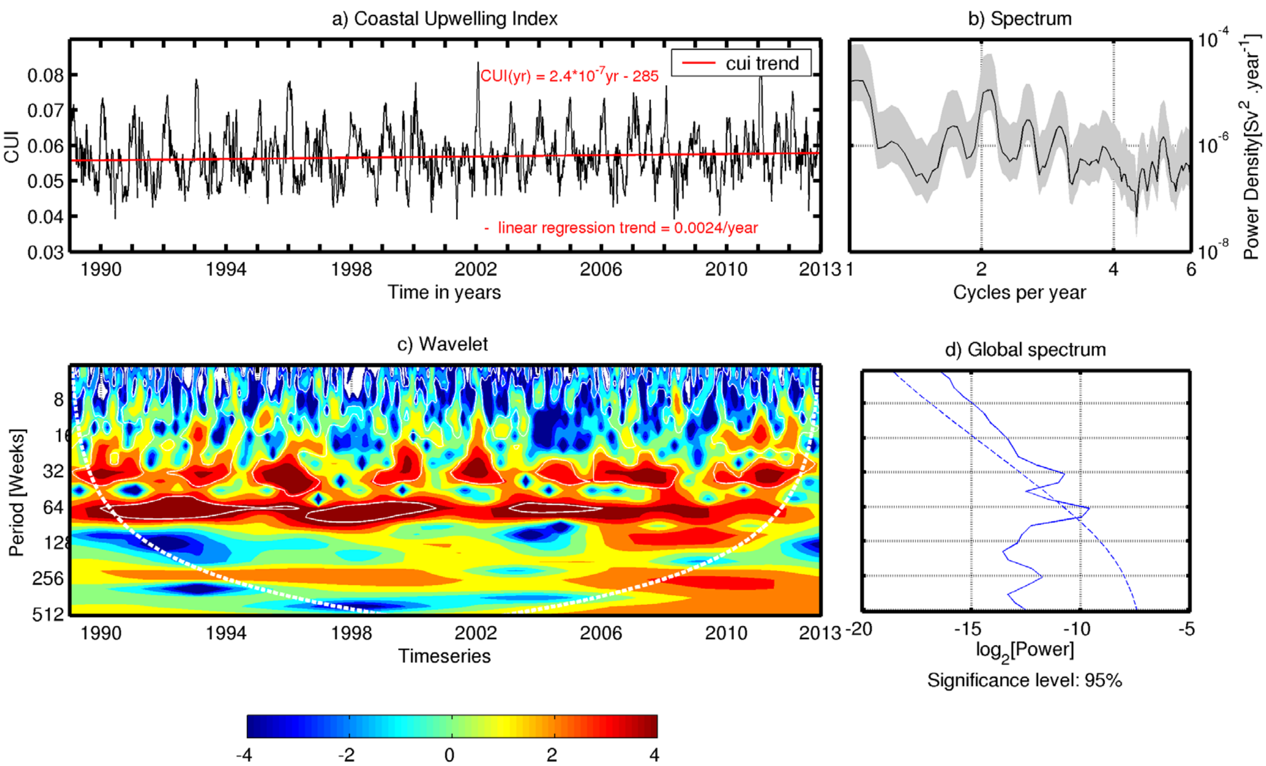


**Figure 8.** a) Model-derived time-series of the coastal upwelling index (CUI) (unitless) estimated from the sea surface temperature (SST) off the coastal city of Tanga in Tanzania, and b) its associated power density spectrum ($Sv^2$ $year^{-1}$) estimated using the multi-taper approach. Panels c) and d) show the wavelet of the CUI and its power spectrum respectively. The red line in a) shows the linear trend of the CUI from 1990 to 2013, with annual rate (0.0024/year ≃ 4%) which follows the equation CUI (yr) = $2.4x10^{-7}$yr - 285. The dashed line in d) shows the confidence line at 95 %.

## SST upwelling index in Tanga

To assess the long-term variability of the upwelling events, the CUI time-series, its power density spectrum, as well as the wavelet transform and its global power spectrum were computed and are presented in Fig. 8. As can be observed in Fig. 8a, the CUI shows high levels of variability with its fluctuating peaks ranging between 0.04 and 0.08. The higher peaks suggest a dominance of an inter-annual variability. In fact, inspection of its power density spectrum computed using the multi-taper approach (Fig. 8b), shows two most dominant peaks of temporal variability, located annually and semi-annually (1 cycle $year^{-1}$ and 2 cycles $year^{-1}$ respectively). The latter could be related to the seasonal reversal of the monsoons (2 monsoons per year) that are known to have a strong influence over the dominant modes of variability in the WIO. In order to inspect other variability patterns, a wavelet signal was analyzed (Fig. 8c). The year versus period plot shows two dominant structures occurring with a periodicity of nearly 32 and 64 weeks. The white dashed line shown in Fig. 8c bounds within it all information which is weighted at a confidence level of 95 %. A notable pattern observed is an intermittent (discontinuous) regular pulse throughout the time-series along a 32-week period, and another continuous pulse at a 64-week period, indicative of inter-annual variability. Their global power spectrum (Fig. 8d) also suggests that the most dominant mode of variability is the inter-annual mode, followed by the seasonal mode.

When a linear regression trend line is fitted onto the time-series of CUI (Fig. 8a), it reveals an overall small upsloping profile that follows the equation CUI(yr) = $2.4x10^{-7}$yr – 285, which suggests that the CUI is slowly intensifying over the years, at a rate of 0.0024 $year^{-1}$ ≃ 4% of the yearly averaged increase. It is likely that this increasing trend can be explained by the observed weak trends of intensification of the wind system in the region (Mahongo *et al.*, 2012), also recently documented by Garcia-Reyes *et al.* [this issue]. Interestingly, the calculated value (0.0024 $year^{-1}$) is comparable with the annual trend estimates (0.002 $year^{-1}$) of another SST based coastal upwelling index derived by Leitão *et al.* (2019), along the Portuguese coast, using remote sensing data (See their Table 3), spanning the years 1985 to 2009.

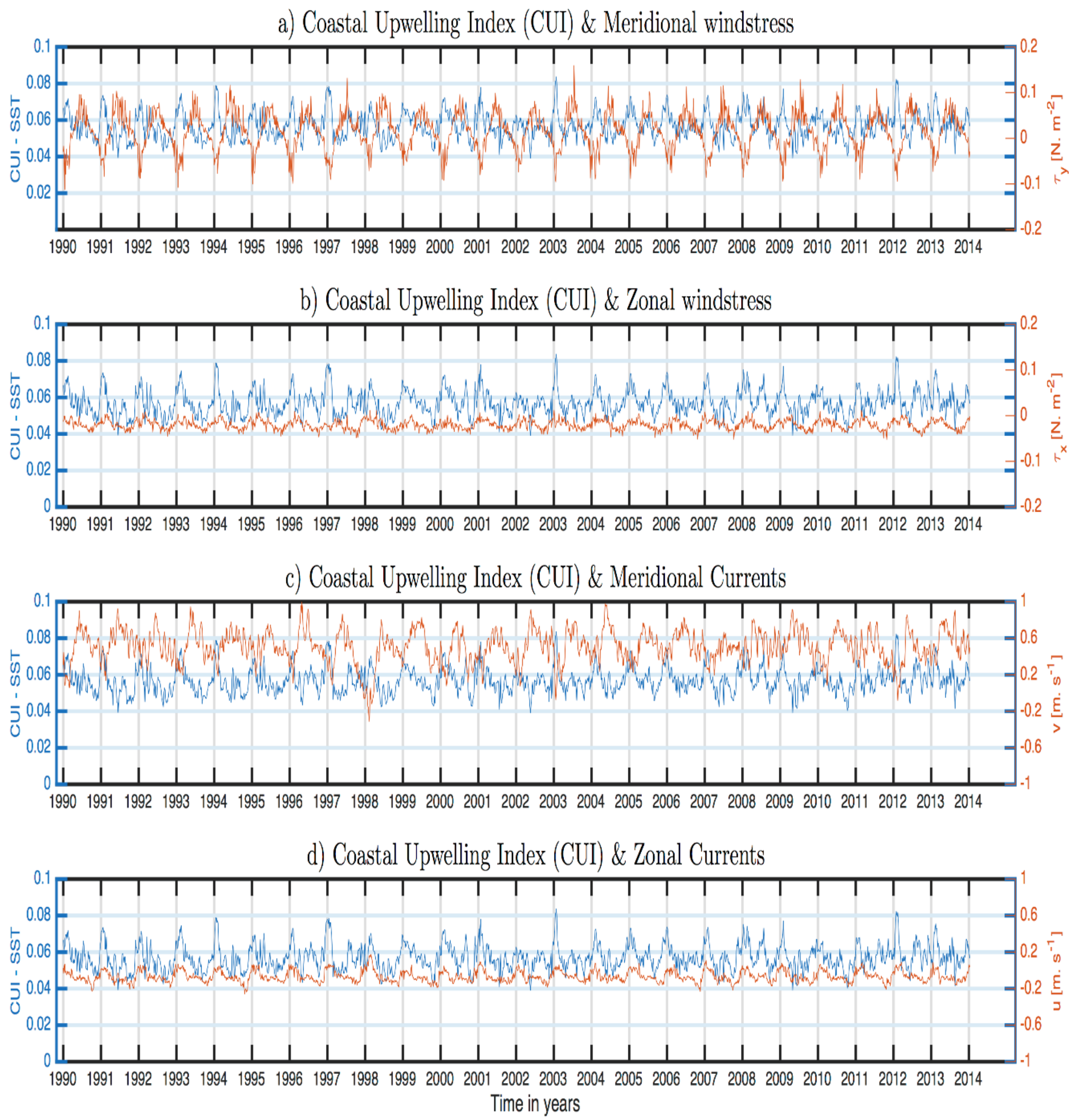


**Figure 9.** Model-derived time-series of the SST coastal upwelling index (CUI) (blue line) (unitless) and a) meridional, b) zonal components of the wind-stress (N $m^{-2}$); and c) meridional, d) zonal components of the ocean surface currents (m $s^{-1}$). For reference see the box positions in Figure 1, used to derive the index.

## Relating winds and currents to the SST upwelling index

To assess the relation between the CUI and atmospheric/oceanic forcing in the EACC region, the model derived time-series of the meridional ($\tau y$) and zonal ($\tau x$) components of the wind-stress, and ocean surface currents ($v$ and $u$) respectively, averaged across the width of the EACC at 6°S (for reference see Fig. 1) were computed, and subsequently, compared against the variability of the CUI derived above. The results are shown in Fig. 9. With regards to the meridional components of the flows, positive (negative) values denote northward (southward) directions respectively. Whereas for zonal components, positive (negative) values indicate eastward (westward) directions respectively.

Fig. 9a reveals a general increase of the CUI, each time coinciding with an intensification of the southward component of the wind-stress (negative $\tau y$). It is also evident that the CUI decreases with an intensification of the northward component of the wind-stress (positive $\tau y$). These results clearly suggest that the upwelling is more developed during the Northeast Monsoons (when the winds are southward oriented), as opposed to the period of the Southwest Monsoon (when the winds are northward oriented). This finding is in agreement with the patterns presented in Fig. 7. To quantify these facts, the statistical correlations between these parameters were performed, and the regression through the scatter plots, and also the strengths of the correlation coefficients (r) analysed, as presented in Fig. 10. Fig. 10a shows a significant ($p < 0.05$), moderate negative linear relationship ($r = -0.53$) between the CUI and the meridional wind-stress $\tau y$, suggesting that the $\tau y$ controls about 28 % of the upwelling variability. On the other hand, no significant relation was found with $\tau x$. The correlation ($r = 0.22$) is weak between the CUI and $\tau x$ (Fig. 10b).

Inspecting Fig. 9c, it is further noticed that CUI has consistently exhibited decreased (increased) tendency each time when the meridional northward current (EACC) velocity increased (decreased) its intensity (Fig. 9c). As would be expected, it is during the Southwest Monsoon when the EACC is strongly intensified in response to the southwest winds, thus both flows (winds and currents) propagate northward (Nyandwi, 2013). On the other hand, a more direct relationship translated by an increased (decreased) tendency of the CUI, equally resulted in an increased (decreased) zonal velocity component of the oceanic currents (Fig. 9d). Statistical analysis in Fig. 10 indicated a low negative ($r = -0.40$, $p<0.05$) linear relationship with a steep slope between the upwelling and the meridional current (v)(Fig. 10-c). It is not clear what the main reason for this could be. However, one may argue this is related to the narrow range of the prevailing local windstress variations. On the other hand, there was a significant ($p<0.05$) and moderate positive ($r = 0.52$) relationship (Assuero *et al.*, 2006), between the upwelling and the zonal components of the current (u), even at very weak current intensities, which ranged around $\pm 0.2$ $ms^{-1}$ (Fig. 10d). This suggests that the reversals of the EACC in an onshore and offshore direction make a significant contribution to the upwelling variability.

## Cross-shore structure of the EACC at 5°S during an upwelling event

To assess the characteristics of the upwelling through the water column with relation to the EACC, an

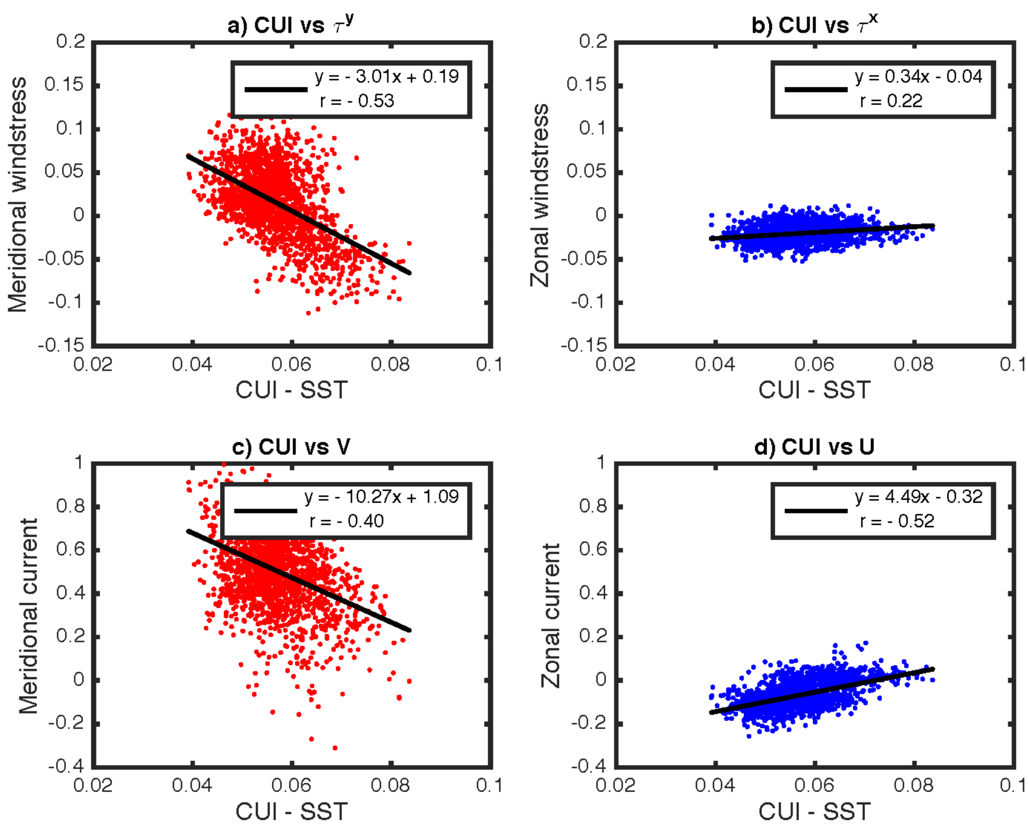


**Figure 10.** Scatter plots of model-derived Pearson correlations between SST coastal upwelling index (CUI [unitless]) against both wind-stress [N. $m^{-2}$], a) meridional, b) zonal components, and ocean currents [m. $s^{-1}$] c) meridional, d) zonal components respectively, along the coast. It also includes the best fit of the linear relationship (y), and correlation coefficients (r), estimated at 95 % confidence.

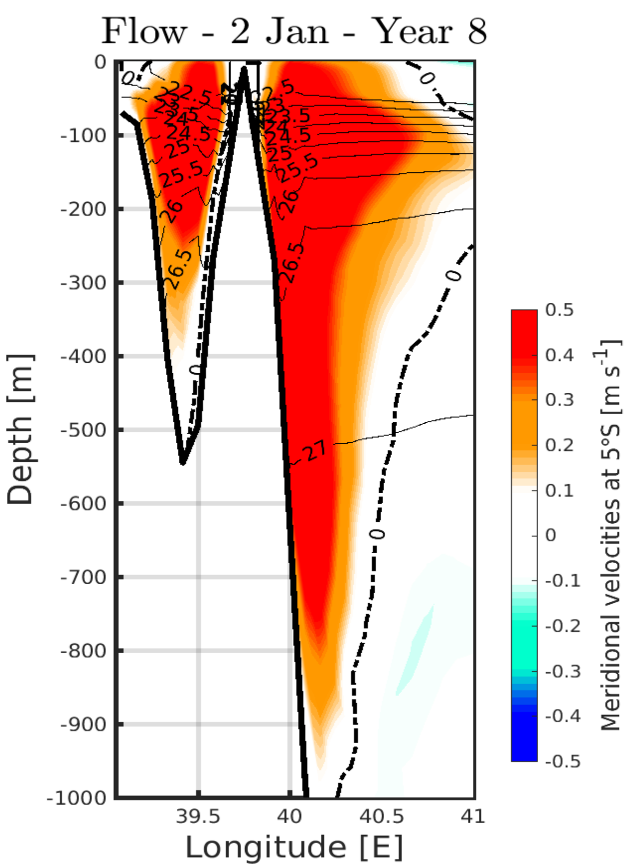


**Figure 11.** Cross vertical section of the model-derived instantaneous meridional flow in m s$^{-1}$, during an active upwelling event on the 2 January Year 8, at 5°S, over a distance spanning from 39 to 41°E. The positive (negative) values indicate northward (southward) directions respectively. The black contours represent the isopycnals (in kg m$^{-3}$) at 0.5 intervals.

instantaneous active upwelling event during the Northeast Monsoon season, occurring on the 2$^{nd}$ of January, model year 8 was selected, and the flow density structure portrayed by the velocity, temperature and salinity properties was inspected. Meridional flow overlaid by potential density is presented in Fig. 11, while potential temperature and salinity is presented in Fig. 12a and Fig. 12b respectively. Positive (negative) values in Fig. 11 denote a northward (southward) direction of propagation, respectively.

Fig. 11 shows two cores of the northward EACC located inshore and offshore. The main core of the inshore flow is approximately between 39.2 and 39.6°E, while the offshore core is between 39.9 and 40.9°E. The inshore core lies within the Pemba Channel, and nearly spans the whole width of the Channel. It has a core velocity of about 0.8 m s$^{-1}$, located almost at the center of the Channel at about 100 m below the sea surface (Fig. 11). A minimum velocity of about 0.1 m s$^{-1}$ is observed at a maximum depth of about 400 m below the sea-surface. On the other hand, the offshore core appears more strongly intensified, with maximum velocities reaching 1 m s$^{-1}$, lying along the continental slope, at about 100 m below the sea-surface. This offshore core is deep reaching, with minimum velocities of about 0.1 m s$^{-1}$ been observed at depths beyond 950 m below the sea-surface (Fig. 11). This pattern of circulation is consistent with the description shown in Fig. 1, and that published by Mahongo and Shaghude (2014), and Mayorga-Adame *et al.* (2016), which support the concept of branching-off of the EACC and recirculation of the flow field around the Zanzibar archipelago. One should note that within the Pemba Channel there is a southward flow (negative values) attached to the eastern boundary slope of the Channel, and it extends throughout the Channel's depth, where it reaches a maximum depth of about 500 m. On the western side of the Channel it is confined only on the upper ~ 30 m, over the shelf. This flow pattern characterized by a northward flow along the continental slope offshore (i.e. eastern flank of the Pemba Island), and a southward flow on-shore (i.e. western flank of the Pemba Island), is a typical characteristic of an anticyclonic recirculation around the Island. Roberts (2015) has indicated that upwelling can be generated by island-wake processes in the region, which usually triggers a pattern similar to that observed in Fig. 11.

Consistently, potential temperature patterns in Fig. 12a reveals uplifting of the isotherms within the Pemba Channel; more notable beyond depths of about 100 m below the sea surface. Conversely, there is evidence of deepening of the isotherms above the 100 m below the sea surface. This suggests the occurrence of a sub-surface upwelling event. Offshore (east of 40°E), along the continental slope, uplifting of the isotherms are more intensified below the depth of 500 m. On the other hand, between the depths of about 50 m and 200 m, the isotherms are nearly zonal and more tightly close together, revealing a relatively strong temperature gradient (Fig. 12a), suggesting a higher stratification. Between 200 m and 500 m depth the isotherms are uplifted offshore and downwelled closer to the continental slope. The isopycnals shown in Fig. 11 also consistently show a similar pattern. This could potentially suggest an inflow of the offshore water toward the coast, as indicated by the isopycnal topography.

Salinity distribution in Fig. 12-b reveals the presence of localized maximum salinity values greater than 35.2 PSU within the Pemba Channel, centered at a depth of about 100 - 150 m below the sea surface. This could

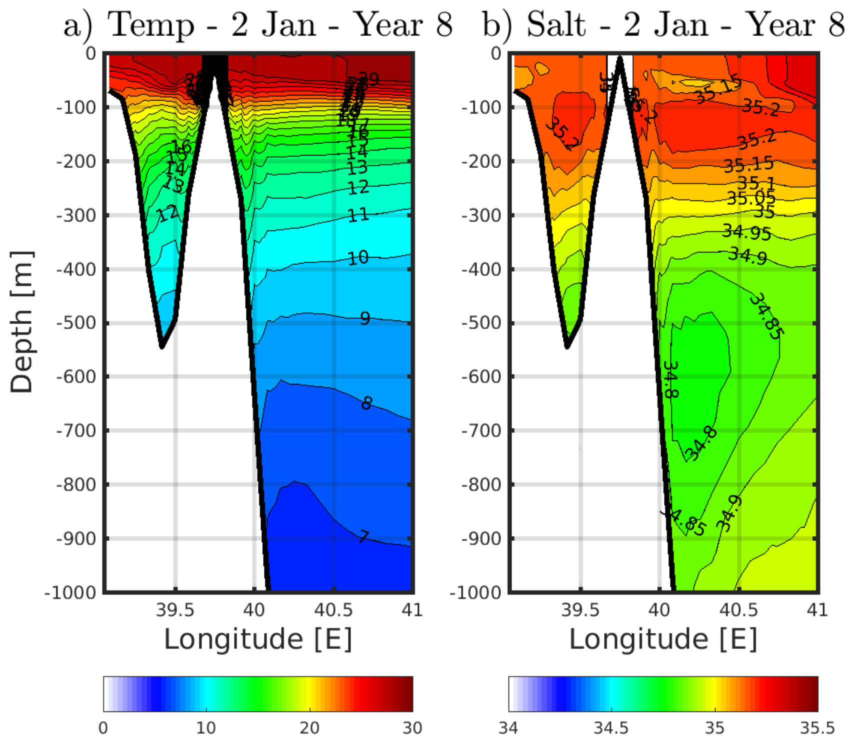


**Figure 12.** Cross vertical section of the model-derived instantaneous hydrographic properties a) temperature (°C) and b) salinity (PSU), during an active upwelling event on the 2 January Year 8, at 5°S, over a distance spanning from 39 to 41°E.

explain the convergence of the isopycnals towards the 100 m layer observed in Fig. 11. It could also possibly explain the blockage of upwelling evolution to reach the sea surface. Thus, stratification appears to be a limiting factor. Looking at the salinity distribution at the offshore environment, it is notable that these high-salinity values are also present at the sea surface to the east of 40.4°E. Here it appears to sink to depths of about 100 m, and then propagates towards the coast between 100 m and 200 m depth. This further corroborates the possibility of a sub-surface westward flow suggested by the westward deepening of the isotherms (Fig. 12a), and slanted isopycnals and velocities in Fig. 11. The modelling study by Manyilizu *et al.* (2014) also revealed an intrusion of offshore tropical western Indian Ocean waters into the Tanzanian coast, dominated by variability on a time-scale of about 5 years.

## Conclusion

In this study a coupled biophysical climatological model and a physical inter-annual simulation run from 1990 to 2013 were used to simulate the upwelling events along the East African coast, off Tanzania and Kenya. The models were able to simulate the circulation and spatial and temporal upwelling variabilities reasonably well, when compared to documented information and in-situ hydrographic measurements. The time-series over the 23 years of the vertically integrated volume transport of the EACC at 6°S on the upper 500 m below the sea surface, plus inspections of its power-spectrum, revealed a consistent positive northward transport, suggesting that the current circulation is permanently northward, regardless of the season, and it is characterized by strong modes of variabilities ranging from intra-seasonal to inter-annual and longer time-scales. This is consistent with the results from previous studies (Swallow *et al.*, 1991; Nyandwi, 2013; Manyilizu *et al.*, 2016).

Surface maps of monthly climatologies of the Ekman derived upwelling phenomena throughout the annual cycle suggested that upwelling along the coasts of Tanzania and Kenya is a normal occurrence. It was manifested more strongly in terms of its intensity and spatial coverage over the east African continental shelf between December and February, which suggests its predominance during the Northeast Monsoon season (Fig. 7a, 7b, 7l). The presence of a persistent localized and small extension of an upwelling cell to the north of Tanzania, around Tanga City, from May to November (period of the Southwest Monsoon, Fig. 7e to 7h), suggests that this upwelling could be driven by a different dynamic process as opposed to that observed during the other season (Fig. 7a, b, l). It is likely that instabilities of the EACC around the chain of islands (Mafia, Unguja, Pemba), and along the continent's lateral boundary play a strong role in creating these upwelling cells, as suggested by direct measurements of the flow field presented by Roberts (2015). In fact, time-series of a SST-based coastal upwelling index suggests both meridional southward winds and zonal variations of the flow along the EACC strongly correlate with the occurrence of the upwelling events by 28% and 27% respectively (Fig. 10). Trend analysis of the coastal upwelling index has shown a small increase (0.0024 year$^{-1}$ $\simeq$ 4%) during the whole modelled period spanning from 1990 to 2013 (Fig. 8a). It is likely that such an increase is related to the general intensification of the volume transport (Fig. 3), and wind system and ocean currents (Mahongo *et al*., 2012; Garcia-Reyes *et al*. [this issue]).

Both wavelet and multi-taper techniques (Fig. 8b, d) also revealed a wide spectral range of the upwelling frequency variability, with dominant signals at inter-annual time-scales. Chlorophyll-*a* distribution patterns in time and space (Fig. 6) suggested that chlorophyll-*a* availability and variability could be modulated by both upwelling events and continental discharges via runoff fluxes. Nevertheless, fundamental questions to assess how the physical processes interact with biological production still need to be answered through future studies.

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## References
Asuero AG, Sayago A, González AG (2006) The correlation coefficient: An overview. Critical Reviews in Analytical Chemistry 36 (1): 41-59 [doi:10.1080/10408340500526766]

Backeberg BC, Penven P, Rouault M (2012) Impact of intensified Indian ocean winds on mesoscale variability in the Agulhas system. Nature Climate Change 2: 608–612 L04604 [doi:10.1038/NCLIMATE1587]

Bakun A (1973) Coastal upwelling indices, west coast of North America. Technical reports 1946 - 71. U. S. Department of Commerce, NOAA Technical Report. NMFS. SSRF. 671pp

Bakun A (1998) Ocean triads and radical interdecadal stock variability: bane and boon for fisheries management. In: Pitcher T, Hart PJB, Pauly D (eds) Reinventing fisheries management. Chapman and Hall, London, UK. pp 331-358

Brink KH, Halpern D, Huyer A, Smith RL (1983) The physical environment of the Peruvian upwelling system. Progress in Oceanography 12: 185-305

Caldwell PC, Merrifield MA, Thompson PR (2015) Sea level measured by tide gauges from global oceans - the Joint Archive for Sea Level holdings (NCEI Accession 0019568, version 5.5. Technical report, NOAA, National Centers for Environmental Information, USA, 42 pp. [doi:10.7289/V5V40S7W]

Capet XJ, Marchesiello P, McWilliams JC (2004) Upwelling response to coastal wind profiles. Geophysical Research Letters 31: L13311 [doi:10.1029/2004GL020123]

Chelton DB, deSzoeke RA, Schlax MG, Naggar KE, Siwertz N (1998) Geographical variability of the first- baroclinic rossby radius of deformation. Journal of Physical Oceanography 28: 433-460

Colas F, McWilliams JC, Capet X, Kurian J (2012) Heat balance and eddies in the Peru-Chile current system. Journal of Climate, Dynamics 39: 509-529 [doi: 10.1007/s00382-011-1170-6]

Collins C, Reason CJC, Hermes JC (2012) Scatterometer and reanalysis wind products over western Tropical Indian Ocean. Journal of Geophysical Research 117: C03045

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. Technical Report, National Oceanographic Data Center, Silver Spring, MD, 392 pp

Cury P, Roy C (1989) Optimal environmental window and pelagic fish recruitment success in upwelling areas. Canadian Journal of Fisheries and Aquatic Sciences 46: 670-680

Da Silva AM, Young CC, Levitus S (1994) Atlas of surface marine data 1994, Vol. 1, algorithms and procedures. Technical Report, U. S. Department of Commerce, NOAA, 83 pp

Dai A, Qian T, Trenberth K, Milliman JD (2009) Changes in continental freshwater discharge from 1948 to 2004. Journal of Climate 22: 2773-2792 [doi: 10.1175/2008JCLI2592.1]

Debreu L, Marchesiello P, Penven P, Cambon G (2012) Two-way nesting in split-explicit ocean models: Algorithms, implementation and validation. Ocean Modelling 49-50: 1-21 [doi: 10.1016/j.ocemod.2012.03.003]

Demarcq H, Faure V (2000) Coastal upwelling and associated retention indices derived from satellite SST. Applications to *Octopus vulgaris* recruitment. Oceanologica Acta 23: 391-408

Durand M-H, Cury P, Mendelssohn R, Roy C, Bakun A, Pauly D (1998) Global versus local changes in upwelling systems. Editions ORSTOM, Paris, France. 558 pp

Echevin V, Marchesiello P, Penven P (2005) Modelisation des regions d'upwelling de bord est a l'aide du systeme Mercator. La lettre trimestrielle Mercator Ocean 18: 18-22

Fasham MJR, Ducklo, HW, McKelvie SM (1990) A nitrogen-based model of plankton dynamics in the oceanic mixed layer. Journal of Geophysical Research 48: 591-639

Gamoio M, Reason C, Collins C (2017) A numerical investigation of the Southern Gyre. Journal of Marine Systems 169: 11-24

Garcia-Reyes M, William JS, David SS, Bryan AB, Albert JS, Steven JB (2015) Under pressure: Climate change, upwelling, and eastern boundary upwelling ecosystems. Frontiers in Marine Science 2 (16): 109 [doi: 10.3389/fmars.2015.00109]

Garcia-Reyes M, Mahongo S (2020) Present and future trends in winds and SST off Central East Africa, [this issue], WIO J. Marine Science.

Gruber N, Frenzel H, Doney SC, Marchesiello P, McWilliams JC, Moisan JR, Oram G-KP, Stolzenbach KD (2006) Simulation of phytoplankton ecosystem dynamics in the California Current System. Deep Sea Research Part I 53 (9): 1483-1516

Leitão F, Vânia B, Vieira V, Silva PL, Relvas P, Teodósio MA (2019) A 60-year time series analyses of the upwelling along the Portuguese coast. Water 11 (1285): 1-26 [doi:10.3390/w11061285]

Lett C, Penven P, Ayon P, Freon P (2007) Enrichment, concentration and retention processes in relation to anchovy (*Engraulis ringens*) eggs and larvae distributions in the northern Humboldt upwelling ecosystem. Journal of Marine Systems 64: 189-200

Mahongo, Francis J, Osima SE (2012) Wind patterns of Coastal Tanzania: their variability and trends. Western Indian Ocean Journal of Marine Science 10(2): 107-120

Mahongo BS, Shaghude YW (2014) Modelling the dynamics of the Tanzanian coastal waters. Journal of Oceanography and Marine Science 5 (1): 1-7 [doi:10.5897/joms2013.0100]

Manyilizu M, Dufois F, Penven P, Reason CJC (2014) Inter-annual variability of sea surface temperature and circulation in the tropical western Indian Ocean. African Journal of Marine Science 36 (2): 233-252 [doi: 10.2989/1814232X.2014.928651]

Manyilizu M, Penven P, Reason CJC (2016) Annual cycle of the upper ocean circulation and properties in the tropical western Indian Ocean. African Journal of Marine Science 38 (1): 81-99 [doi: 10.2989/1814232X.2016.1158123]

Manyilizu M, Sagero P, Halo I, Mahongo S (2020) Inter-annual relationship of SST and upper-ocean circulation between northern Tanzania and northern Kenya Bank [This issue], WIO J. Marine Science.

Mapunda XE (1983) Fisheries economics in the context of the artisanal fisheries of the marine sector. Technical report, TAFIRI. SWIOP Document OISO. RAF/79/065/WP/7/83, 6 p

Marchesiello P, Estrade P (2010) Upwelling limitation by inshore geostrophic flow. Journal of Marine Research 68: 37-62

Mayorga-Adame CG, Ted-Strub TP, Batchelder HP, Spitz YH (2016) Characterizing the circulation off the Kenyan-Tanzanian coast using an ocean model. Journal of Geophysical Researchs 121: 1377-1399 [doi:10.1002/2015JC010860]

Ministry of Agriculture Livestock and Fisheries (2016) The Tanzanian fisheries sector: Challenges and opportunities. Technical report, Ministry of Agriculture Livestock and Fisheries, 40 pp

Nyandwi N (2013) The effects of monsoons on the East African Coastal Current through the Zanzibar Channel, Tanzania. Journal of Ocean Technology 8 (4): 65-74

Penven P, Marchesiello P, Debreu L, Lefe`vre J (2008) Software tools for pre- and post-processing of oceanic regional simulations. Environmental Modelling and Software 23: 660-662 [doi: 10.1016/j.envsoft.2007.07.004]

Peter JSF (2002) NPZ models of plankton dynamics: Their construction, coupling to physics, and application. Journal of Oceanography Review 58: 379-387

Ramanantsoa JD, Krug M, Penven P, Rouault M, Gula J (2018) Coastal upwelling south of Madagascar: Temporal and spatial variability. Journal of Marine Systems 178: 29–37 [doi: 10.1016/jmarsys.2017.10.005]

Ridgway KR, Dunn JR, Wilkin JL (2002) Ocean interpolation by four-dimensional least squares - Application to the waters around Australia. Journal of Atmospheric and Oceanic Technology. 19: 1357-1375 [doi: 10.1175/15200426(2002)019]

Rio MH, Guinehut S, Larnicol G (2011) The new CNES-CLS09 global mean dynamic topography computed from the combination of GRACE data, altimetry and in-situ measurements. Journal of Geophysical Research 116: C07018 [doi: 10.1029/2010JC006505]

Rio M-H, Hernandez F (2004) A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model. Journal of Geophysical Research 109: C12032

Risien C, Chelton DB (2008) A global climatology of surface wind and wind stress fields from eight years of QuikSCAT Scatterometer data. Journal of Physical Oceanography 38: 2379-2413 [doi:10.1175/2008JPO3881.1]

Roberts MJ (2015) The western Indian Ocean upwelling research initiative (WIOURI): A flagship IIOE2 project. Clivar Exchange 68, 19 (3): 26-30

Roxy M, Ritika, K, Terray P, Masson S (2014) The curious case of Indian Ocean warming. Journal of Climatology 9: 8501-8509

Schott FA, Fieux M, Kindle J, Swallow J, Zantopp R (1988) The boundary currents east and north of Madagascar: 2 Direct measurements and model comparisons. Journal of Geophysical Research 93: 4963-4974

Schott FA, Shang-Ping X, McCreary JP (2009) Indian Ocean climate variability. Reviews of Geophysics 47: RG1002 (1–46) [doi: 10.1029/2007RG000245]

Shchepetkin AF, McWilliams JC (2005) The regional oceanic modeling system (ROMS): a split- explicit, free-surface, topography-following-coordinate oceanic model. Ocean Modelling 9: 347-404 [doi:10.1016/j.ocemod.2004.08.002]

Smith-Boughner L, Constable C (2012) Spectral estimation for geophysical time-series with inconvenient gaps. Geophysical Journal International 190: 1404-1422 [doi:10.1111/J.1365-246X.2012. 05594.X]

Swallow J, Schott FA, Fieux M (1991) Structure and transport of the East African Coastal Current. Journal of Geophysical Research 93: 4951-4962

Thomson D.J (1982) Spectrum estimation and harmonic analysis, Proceedings. Institute of Electrical Electronics Engineers 70, 1055-1096

# Present and future trends in winds and SST off central East Africa

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## Abstract

The coast of central East Africa (CEA) is a dynamic region in terms of climate, in which fisheries and marine-related services impact a large portion of the population. The main driver of regional dynamics is the seasonal alternation of the Northeast (NE) and Southeast (SE) monsoons. Winds associated with these monsoons modulate the prevalent, remotely-forced East African Coastal Current (EACC). Here, present and future trends in winds and sea surface temperature (SST) of the CEA and adjacent regions are investigated using reanalysis and reconstructed data, and an ensemble of General Circulation Models. It was found that the winds and SST show unidirectional trends, with magnitude and spatial differences between the NE and SE monsoons. Winds show weakening trends during the NE monsoon, in the past and future, of the Somali region; with no significant trends during the SE monsoon. SST shows increasing trends in the entire region in the past and future, with stronger warming during the NE monsoon off Somalia; SST trends are smaller in the CEA. These trends could impact the CEA through increased water-column stability and decreased upwelling due to shifting of the EACC separation from the continent. However, given the coarse resolution of data analyzed, regional modeling is still necessary to understand the impacts on local dynamics and productivity in the CEA.

**Keywords:** Wind trends, SST trends, Eastern African coastal current, East African monsoon, Climate change, Somali current

## Introduction

The region encompassing the coasts of Kenya and Tanzania and their islands, referred to here as Central East Africa (CEA), is a highly dynamic, remotely forced coastal region. The CEA is embedded in the northward East African Coastal Current (EACC), which is the northward extension of the South Equatorial Current (SEC) that passes the northern tip of Madagascar before reaching the African continent (Schott and McCreary, 2001; Manyilizu *et al.*, 2016); the strength of the EACC and the CEA regional climate depend on the seasonal shift in the Inter-Tropical Convergence Zone that drives the Northeast (NE) and Southeast (SE) monsoons (McClanahan, 1988). During the NE monsoon, from December to February, the EACC is slower and warmer, reaching its highest temperatures in March-April; during the SE monsoon, from April to October, the EACC is faster, cooler and saltier, with a minimum temperature around September (McClanahan, 1988; Mahongo and Shaghude, 2014; Manyilizu *et al.*, 2016). In both seasons, low nutrient water from the SEC (Jury *et al.*, 2010) flows northward along the coast where it is enriched and mixed by local dynamics: island's wake upwelling (Roberts *et al.*, 2008), wind-driven downwelling (McClanahan, 1988), Ekman divergence and convergence (Manyilizu *et al.*, 2016), rainfall and runoff (McClanahan, 1988), upwelling due to the separation of the EACC from the continent off northern Kenya where it meets the southward Somali Current during the NE monsoon (Manyilizu *et al.*, 2016), and tidal dynamics in between the mainland and the islands (Zavala-Garay *et al.*, 2015).

The CEA region is also densely populated where fisheries (commercial, artisanal and recreational), and marine-related tourism services impact a large portion of the population (van der Elst *et al.*, 2005; FAO, 2018). Changes in environmental conditions due to climate change is likely to increase pressure on the local marine ecosystems, already stressed by growing

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populations and extensive fisheries (van der Elst *et al*., 2005). Understanding how environmental conditions are and will be impacted by a changing climate is a first and necessary step in developing, managing and adaptation strategies for this region. Unfortunately, local studies of environmental change are limited due to sparse availability of data, both oceanographic and atmospheric, and while local modeling efforts that accurately represent seasonal variability in the CEA exist (Mahongo and Shaghude, 2014; Zavala-Garay, 2015), projections of the future conditions are still not available at such scales. There is evidence however, that coastal winds off the coast of Tanzania have increased in the past three decades (Mahongo *et al*., 2012); although off north Kenya NE monsoon winds appear to be decreasing (Varela *et al*., 2015). Given the remotely forced nature of the EACC and the monsoons, it is possible to investigate past and future changes in regional wind circulation with climate change using an ensemble of General Circulation Models (GCM), and gain insight into coastal conditions. Additionally, changes in regional sea surface temperature (SST), an indicator highly linked to the monsoon dynamic and the EACC at the coast, provides regional context for oceanographic change with climate. In this study, it is hypothesized that changes in winds and SST in the region show unidirectional trends consistent with global warming, but that trends differ between the monsoons leading to changes in the regional seasonal cycle in the EACC.

## Data and methods

The area of study was delimited by 15°S to 5°N and 35°E to 55°E, which covers the EACC, the western end north fork of the SEC, passing north of Madagascar, and the southern part of the Somali Current. Monthly wind vectors at 10 m and monthly SST data were analyzed for past and future linear trends. To investigate

**Table 1.** General Circulation Model List.

| Model Name | Source |
|---|---|
| ACCESS1-0 | Australian Weather and Climate Research |
| ACCESS1.3 | " |
| BCC-CSM1-1 | Beijing Climate Center, China Meteorological Administration |
| BCC-CSM1-1m | " |
| CanESM2 | Canadian Centre for Climate Modelling and Analysis |
| CESM1-BGC | National Center for Atmospheric Research, USA |
| CMCC-CESM | Centro Euro-Mediterraneo sui Cambianenti Climatici, Italy |
| CMCC-CS | " |
| CMCC-CMS | " |
| CNRM-CM5 | Centre National de Recherches Meteorologiques, France |
| CSIRO-Mk3-6 | Australian Commonwealth Scientific and Industrial Research Organisation |
| GFDL-CM3 | Geophysical Fluid Dynamics Laboratory, USA |
| GFDL-ESM2M | |
| HadGEM2-AO | Met Office Hadley Centre, UK |
| IPSL-CM5A-LR | Institut Pierre-Simon Laplace, France |
| IPSL-CM5A-MR | " |
| IPSL-CM5B-LR | " |
| MIROC5 | Atmosphere and Ocean Research Institute, University of Tokyo, Japan |
| MPI-ESM-LR | Max Planck Institute for Meteorology, Germany |
| MPI-ESM-MR | " |
| MRI-CGCM3 | Meteorological Research Institute, Japan |
| MRI-ESM1 | " |

past trends, wind vectors from 20th Century Reanalysis V3 (20CR) was obtained from the National Ocean and Atmospheric Administration (NOAA/CIRES/DOE/ESRL PSD, Boulder, Colorado, USA) available at https://www.esrl.noaa.gov/psd, and SST data from the HadISST1 (HadSST) reconstruction dataset provided by the Meteorological Office Hadley Centre in the UK, available at https://www.metoffice.gov.uk/hadobs/hadisst/. 20CR provides 1 degree resolution wind data through a single assimilated model that runs for the entire available time period (Compo *et al.*, 2011); 20CR assimilates SST data from the HadSST dataset, which provides reconstructed data with a resolution of 1 degree (Rayner *et al.*, 2003). Data were obtained for the period 1950 to 2015. In addition, wind vectors and SST data from an ensemble of GCM, part of the Intercomparison model project (CMIP5, Taylor *et al.* 2012) used in the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5) and available at https://cmip.llnl.gov/cmip5/, were obtained for the historical period (1950 to 2005) and compared to 20CR and HadSST data. Data was also obtained from future projections to estimate future trends under climate change for the period 2006 to 2100, with a simulation that uses the representative concentration path (RCP) 8.5, which represents a "business as usual" scenario in terms of green-house gas emissions and concentrations (IPCC, 2013). From the CMIP5 models, 22 were selected (Table 1) that accurately (qualitatively) represent the seasonality of SST and wind stress compared to HadSST and 20CR. To be able to compare GCM data among them and with HadSST and 20CR, they are scaled to a uniform 1-degree grid, since they all have different resolution and grids.

Based on the seasonality exhibited by the 20CR data, and compared with the description in Mahongo *et al.* (2012), the monsoons were selected as: Northeast monsoon from December to February and Southeast monsoon from April to October; however, DJF averages for the NE monsoon and MJJA averages for the SE monsoon were used to represent seasonal contrast. Analysis trends were performed over NE or SE monsoon annual averages calculated for each grid point, from 1950 to 2015 for the observations, from 1950 to 2005 for the GCMs historical simulations, and from 2006 to 2100 for future projections. Trends for zonal and meridional components of winds were calculated

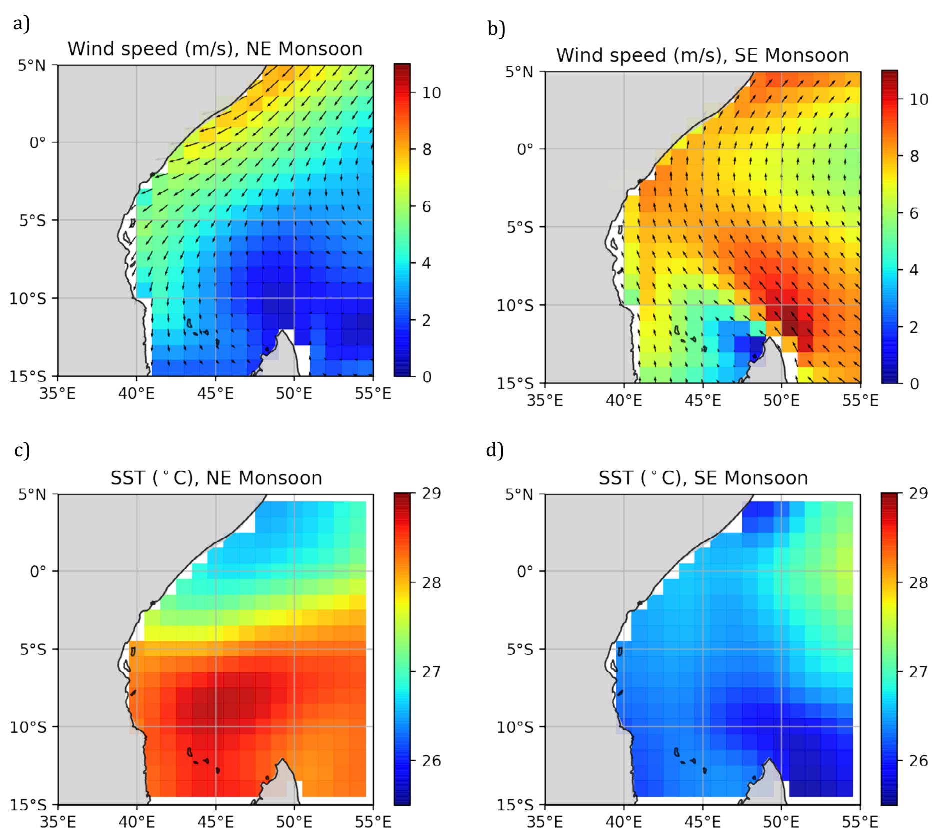


**Figure 1.** Climatology of SST (HadISST1 Reconstruction, bottom) and wind speed vectors (20th Century Reanalysis, top) for Northeast (NE, left) and Southeast (SE, right) monsoons from 1950-2015.

separately. To estimate trends, a linear regression was fitted to each time series of each grid point. Linear trends were chosen because they represent an estimate of rate and sign of change that is easier to interpret and represent in spatially-explicit analysis. Significant trends are considered for p-values < 0.05. For GCM, a significant trend was considered for a given location if the ensemble had 10 or more models showing a significant trend (p<0.05) for a given grid point, after which the significant trends from individual models were averaged. To further evaluate the significance of trends in the GCMs, signal to noise ratios (SNR) were calculated and locations with SNR values < 1 were considered non-significant. SNR were calculated by dividing the mean trend value of all models exhibiting significant trends (only where 10 or more are significant) by the standard deviation of those trends (noise). All analyses were performed in Python 3.

## Results

The climatology (Fig. 1) of wind shows that the NE monsoon winds are limited to the coast, and strongest off the Somalia coast, consistent with cooler temperatures, decreasing in the CEA, and weak or zero in the north and east of Madagascar. SST shows warmer temperatures below 4°S. During the SE monsoon, winds are prevailing from the south in the entire region, but weaker in the CEA, east of Madagascar and the northeast area. SST is more uniform during the SE monsoon, only warm toward the northeast of the region where winds are weak and with a colder signature of the SEC and the upwelling area off Somalia.

Historical trends in 20CR data (Fig. 2) indicates that during the NE monsoon zonal winds show a positive trend on the northeastern part of the domain. Since the prevailing winds at this time are largely from the northeast or north, these trends represent a shift toward more meridional winds, and slightly weaker (since no change in the meridional component was found) in the outer border of the coastal jet (Fig. 1). During the SE monsoon, only a small portion of the north coast shows increasing zonal winds, associated with the SEC and the Somali Current, indicating

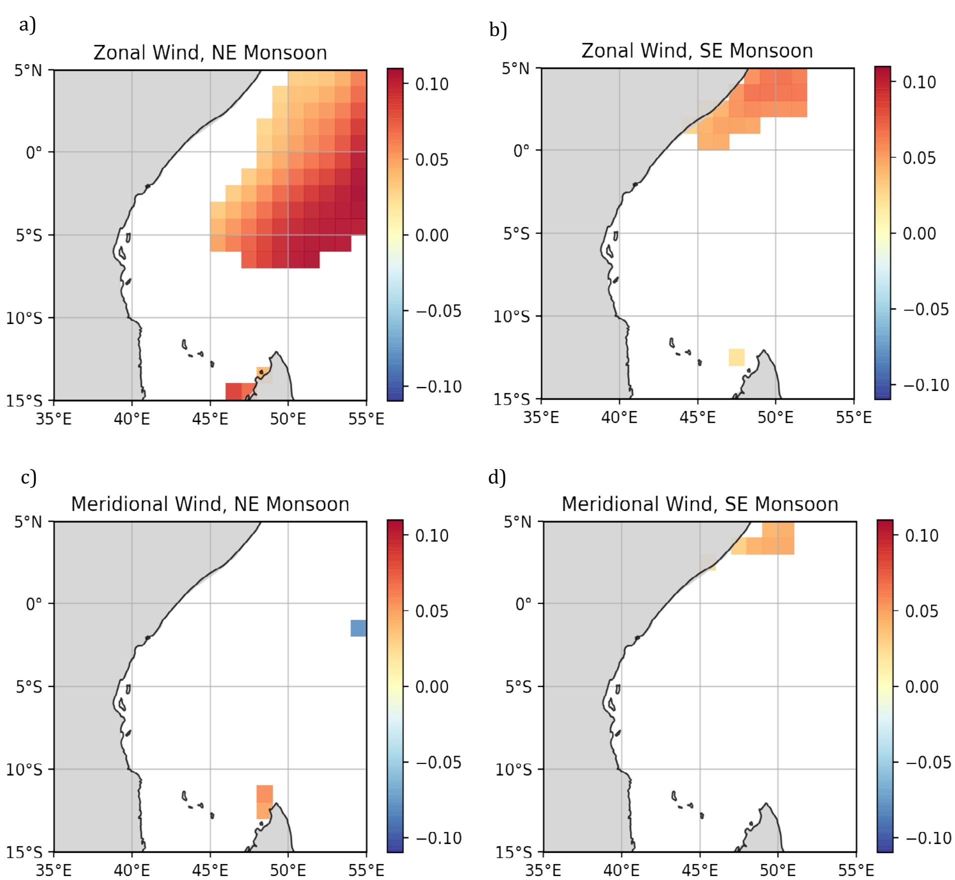


**Figure 2.** Linear trends in zonal (top) and meridional (bottom) wind speed from the 20th Century Reanalysis, for both NE (left) and SE (right) monsoon seasons for the period 1950-2015. Units in m/s/decade. Only significant (p<0.05) trends are shown.

a limited strengthening of the zonal winds in this region. No significant changes were found for the meridional winds (Fig. 2b, d). In contrast, data from the GCM ensemble do not show significant trends for the historical period anywhere in the study domain (not shown). HadSST data shows increasing trends in most of the domain in both monsoons, except a small area north of Madagascar (Fig. 3a, b). Largest trends (~0.2°C/decade) were found in the eastern equatorial region of the domain during the SE monsoon, and in the center and south western area during the NE monsoon (~0.14°C/decade). GCM historical data also show significant increasing trends in SST during both monsoons (Fig. 3c, d), with SST increasing in the northern region of the domain (~0.12°C/decade) in the Somali Current region, and lowest in the CEA during the NE monsoon. Non-significant SST trends occur on the northeast side of Madagascar, and along the Tanzanian coast. During the SE monsoon, in contrast with the HadSST data, largest trends are observed in the

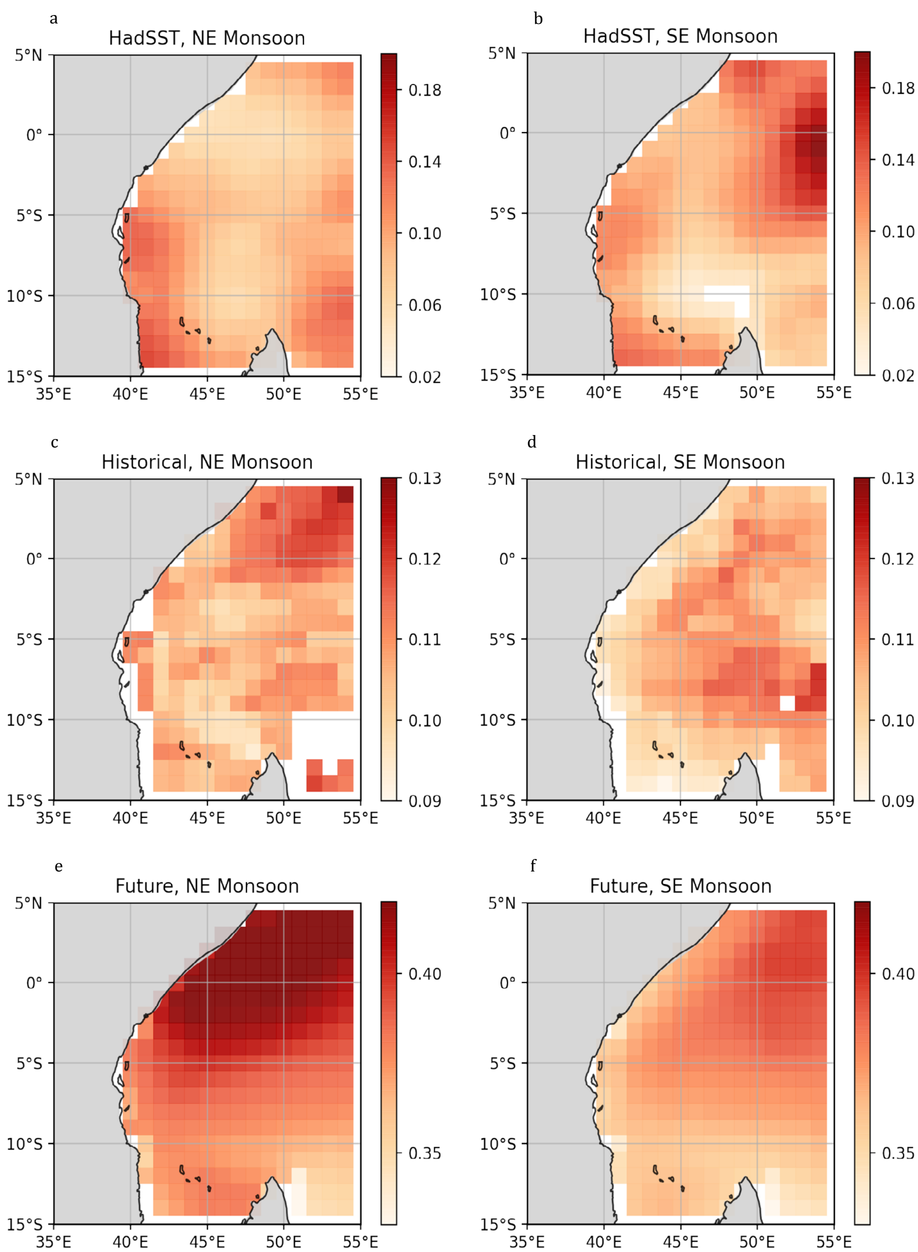


**Figure 3.** Linear trends in SST for NE (left) and SE (right) monsoon seasons. Top panels: HadISST1; Only significant ($p<0.05$) are shown. Middle panels: GCM ensemble mean for the historical simulations; Bottom panels: GCM ensemble mean for future projections. Only mean values of 10 or more models showing significant ($p<0.05$) trends, and with signal to noise ratio values > 1 are shown.

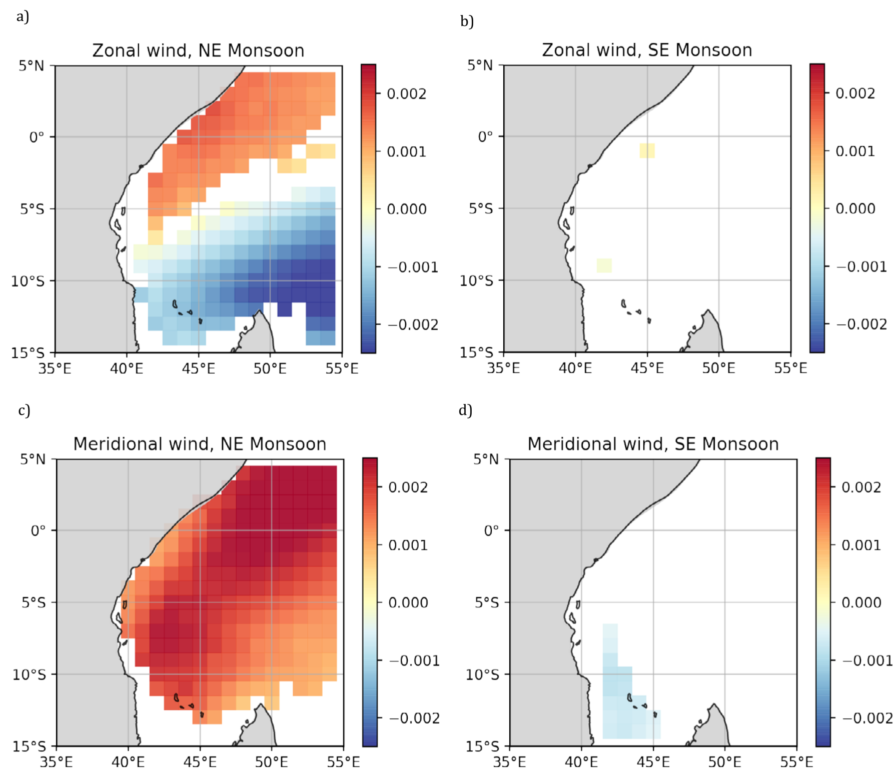


**Figure 4.** Future trends in wind stress (a) and signal to noise ratio (b) for the NE monsoon for the GCMs ensemble data. Only mean values of 10 or more models showing significant ($p<0.05$) trends are shown. Linear trends in zonal (top) and meridional (bottom) wind speed for GCMs ensemble future projections, for both NE (left) and SE (right) monsoon seasons for the period 2006-2100. Units in m/s/decade. Only mean values of 10 or more models showing significant ($p<0.05$) trends, and with signal to noise ratio values > 1 are shown.

central/southern eastern areas of the domain (~0.12°C/decade). Despite these differences, GMC data show a small range of trends (0.09-0.13°C/decade) within the domain, while HadSST shows a wider range, from 0.02 to 0.18°C/decade.

Future trends of winds in GCM show increasing zonal and meridional wind speed during the NE monsoon, mainly in the Somali Current region (Fig. 4a, c), which suggest weakening of the prevailing winds. This region corresponds with the region of largest SST trends (up to 0.42°C/decade, Fig. 3e) in future projections. A region of decreased zonal winds and slightly increased meridional winds is observed south of 5ºS, a region with very weak climatological winds during this monsoon. During the SE monsoon, no significant trends in winds were found (Fig. 4b, d), except for weak negative trends in meridional in the southwest area. Future SST show increasing trends in the entire domain with stronger trends in the northeast corner of the domain (Fig. 3e, f), but weaker than during the NE monsoon. The range in SST trends is larger in the NE monsoon, both with minima of 0.34°C/decade in the southeast corner to >0.4°C/decade in the northern area for NE, and < 0.4 for SE. Notably, smaller trends in SST are found in the CEA.

## Discussion

SST off the coast of CEA shows significant increasing trends in the last several decades as well as in future projections under anthropogenic climate change, with differences between the two monsoons, as hypothesized. Wind speed shows statistically significant trends, in the observational record, in the zonal wind for the NE monsoon, and in a small area for the SE monsoon in both zonal and meridional components. However, these trends are not replicated in the historical simulations of the climate models. In the last century, wind, the physical feature that experiences the largest variability during the year, shows significant trends only in the zonal component off the eastern side of the Somalia jet during the NE monsoon – a region with weak or zero zonal wind in the climatology. These trends indicate that the wind shows a shift toward a more meridional direction of the wind in these regions during the NE monsoon, but no change at the coast, differing from the weakening trends shown by Varela *et al.* (2015) using CSFR reanalysis data. During the SE monsoon, zonal wind has increased slightly off Somalia, strengthening the seasonal winds. Notable, these trends are not replicated in the GCM, which does not show significant trends in either monsoon. This might be due to the small long-term changes in comparison with the large variability between models. SST, on the other hand, shows significant warming during the period of study in both observational data and GCM for both monsoons, although with spatial differences. During the NE monsoon both GCM data show larger trends off Somalia, while 20CR data shows larger trends in the opposite corner of the domain. During the SE monsoon however, observations show larger trends in the eastern side of the region, while the GCMs show larger trends in the central north. While increasing SST is the dominating signal in the entire region, and they differ between model and reanalysis, trends differ between seasons in each dataset, with the historical data showing the largest trends in SST during the NE monsoon, in the same region of weakening winds.

GCM future trends, under the "business as usual" carbon path model, showed larger trends than in the last century. First, winds show significant trends in zonal and meridional winds only during the NE monsoon, indicating weakening northeast winds (as the prevailing direction is negative in both zonal and meridional components, positive trends indicate weakening of the winds), particularly in the north; these results are consistent with those found in the reanalysis data for the zonal wind. Note that the magnitude of the trends in the GCM data is small, which reflects the large variability of magnitudes (and signs) among models. The coastal regions show no significant trends in the zonal component of the wind, which is possibly a combination of small trends and low model resolution. Notably, no significant trends are projected for the SE monsoon, and only weak and sparse ones are observed in the 1950-2015 reanalysis data, despite other studies reporting trends in observations for the last decades (Mahongo *et al.*, 2012). SST future trends show magnitudes up to 3 times larger than those in the 1950-2015 period, and in both monsoons, trends are smaller at the CEA southern areas. The largest SST trends are during the NE monsoon in the Somali Current region, consistent with the weakening trend in winds in this region during this season, which potentially increase the warming trends by reducing mixing.

The findings presented here suggest increased water column stability from increasing SST, especially during the NE monsoon. McClanahan (1988) indicated that the stability already observed in this season is important for biological productivity, although it is unclear if increased stability would be favourable. A potential consequence of the trends in the wind during the NE monsoon is a northward shifting of the EACC separation from the continent, where the northward flowing EACC and the southward flowing Somali Current meet, due to weakening winds. This could also shift the upwelling occurring at the coast due to the separation of these current from the coast, potentially reducing the entrainment of nutrients around Northern Kenya. However, nitrate rich water from fixation by algae (McClanahan, 1988) and island wake upwelling from Tanzanian and Kenyan islands (Roberts *et al.*, 2008) might be reaching further north as the EACC reaches further north, partially compensating for the reduced upwelling. Given the resolution of the data analyzed here, a regional modeling analysis of currents and water characteristics under present and future climate would provide a more accurate insight on these changes and their implications for local conditions (see Halo *et al.*, 2020, in this issue).

Finally, while consistent future changes in weakening winds and increasing SST during the NE monsoon were found in this analysis, during the SE monsoon only SST show significant increasing trends. However, given observed increasing trends (in this analysis during the SE monsoon on 20CR data and those reported by Mahongo *et al.* (2012) year-round), it would be worth further investigating the interannual to decadal variability in the conditions during this monsoon, which seems to be large and associated with climate oscillations (Mahongo *et al.*, 2012), and it might have the largest implications for the marine ecosystem.

## Acknowledgements

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## References

Compo GP, Whitaker JS, Sardeshmukh PD, Matsui N, Allan RJ, Yin X, Gleason BE, Vose RS, Rutledge G, Bessemoulin P, Brönnimann S, Brunet M, Crouthamel RI, Grant AN, Groisman PY, Jones PD, Kruk MC, Kruger AC, Marshall GJ, Maugeri M, Mok HY, Norfli O, Ross TF, Trigo RM, Wang XL, Woodruff SD, Worley SJ (2011) The Twentieth Century

Reanalysis Project. Quarterly Journal of the Royal Meteorological Society 137: 1-28

FAO (2018) Fishery and aquaculture country profiles. Kenya (2016). Country Profile Fact Sheets. In: FAO Fisheries and Aquaculture Department [online], Rome [http://www.fao.org/fishery/]

IPCC (2013) Climate change 2013: The physical science basis. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York. 1535 pp [doi:10.1017/CBO9781107415324]

Halo I, Sagero, P, Majuto M, Mahongo S (2020) Biophysical modelling of the coastal upwelling variability and circulation along the Tanzanian and Kenyan coasts. Western Indian Ocean Journal of Marine Science, Special Issue 1/2020: PAGS

Jury M, McClanahan T, Maina J (2010) West Indian Ocean variability and East African fish catch. Marine Environmental Research 70: 162-170

Mahongo SB, Francis J, Osima SE (2012) Wind patterns of coastal Tanzania: Their variability and trends. Western Indian Ocean Journal of Marine Science 10 (2): 107-120

Mahongo SB, Shaghude YW (2014) Modelling the dynamics of the Tanzanian coastal waters. Journal of Oceanography and Marine Sciences 5 (1): 1-7

Manyilizu M, Peven P, Reason CJC (2016) Annual cycle of the upper-ocean circulation and properties in the tropical western Indian Ocean. African Journal of Marine Science 38 (1): 81-99

McClanahan T (1988) Seasonality in East Africa's coastal waters. Marine Ecology Progress Series 44: 191-199

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. Journal of Geophysical Research 108 (D14). 4407 pp

Roberts MJ, Ribbink AJ, Morris T, Duncan F, Barlow R, Kaelher S, Huggett J, Kyewalyanga M, Harding R, Van den Berg M (2008) 2007 Western Indian Ocean cruise and data report: Alg 160. African Coelacanth Ecosystem Programme, Grahamstown. 130 pp

Schott FA, McCreary Jr JP (2001) The monsoon circulation of the Indian Ocean. Progress in Oceanography 51 (1): 1-123

Taylor KE, Stouffer RJ, Meehl GA (2012) An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society 93: 485-498

Van der Elst R, Everett B, Jiddawi N, Mwatha G, Afonso PS, Boulle D (2005) Fish, fishers and fisheries of the Western Indian Ocean: their diversity and status. A preliminary assessment. Philosophical Transactions of the Royal Society A 363: 263-284

Varela R (2015) Has upwelling strengthened along worldwide coasts over 1982-2010? Nature Scientific Reports 5 (10016)

Zavala-Garay J, Theiss J, Moulton M, Walsh C, van Woesik R, Mayorga-Adame CG, García-Reyes M, Mukaka DS, Whilden K, Shaghude YW (2015) On the dynamics of the Zanzibar Channel. Journal of Geophysical Research – Oceans 120: 6091-6113

# Preliminary findings on the food and feeding dynamics of the anchovy *Stolephorus commersonnii* (Lacepède, 1803) and the Indian mackerel *Rastrelliger kanagurta* (Cuvier, 1817) from Tanga Region, Tanzania

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## Abstract

Small pelagic fishes play an important role in the ecosystem by linking planktonic production and higher trophic level predators, and provide a livelihood to both the small-scale and commercial fisher communities. This study analyzed the food and feeding habits of *Stolephorus commersonnii* (Lacepède, 1803) and *Rastrelliger kanagurta* (Cuvier, 1817) from the ring-net fishery in Tanga, Tanzania. A total of 1 434 and 320 stomachs of *S. commersonnii* and *R. kanagurta* respectively were examined for gut contents using the relative volumetric method. *S. commersonnii* was found to be a planktivorous carnivore, feeding principally on planktonic penaeid shrimps (48.6%), fish larvae (33.2%) and zooplankton (12.3%). *R. kanagurta* was found to be carnivorous, feeding predominantly on fish (60.6 %), mainly *S. commersonnii*, while penaeid shrimps, juvenile fish, and juvenile stages of squids formed 26.5% of the total number of food items in *R. kanagurta* guts. Both *S. commersonnii* and *R. kanagurta* exhibited ontogenic diet shifts, where they fed exclusively on small prey as juveniles and consumed larger food items as they grew. The index of vacuity was higher in *S. commersonnii* (46.1%) than in *R. kanagurta* (16.6%). This study revealed the importance of penaeid shrimps as food for *S. commersonnii*, that in turn formed the main food for *R. kanagurta*. This implied that the two species were able to coexist in the same niche by avoiding interspecific competition for food.

**Keywords:** Food and feeding, *Stolephorus commersonnii, Rastrelliger kanagurta,* Small pelagics, Tanga, Tanzania

## Introduction

Small pelagic fishes are of global importance both socio-economically and ecologically. Small pelagic fisheries contribute over 50% of the world's wild-caught catches (Cury *et al*., 2000). Ecologically, small pelagic fishes play a crucial role because they can constitute such large biomass in pelagic systems that they have the capacity to exert strong bottom up or top down control (Raab *et al*., 2011). The fishery for small pelagics makes a substantial contribution to catches by commercial and artisanal fishers in the United Republic of Tanzania (Bodiguel *et al.*, 2015), and many other tropical and subtropical countries (van der Lingen *et al.*, 2006). Furthermore, the Tanzanian fishery plays a significant role in job creation and food security, with participation being affordable at all socio-economic levels. Bodiguel *et al.* (2015) estimated that around 10,000 people in both mainland

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Tanzania and Zanzibar are directly engaged in the small pelagic fishery and related activities (fishers, porters, boiling and drying workers, processing entrepreneurs, traders, wood and salt suppliers, transporters and food vendors).

The findings of this study are part of the *"Responses of biological Productivity and fisheries to changes in atmospheric and oceanographic conditions in the upwelling region associated with the East African Coastal Current"* (PEACC) project which sought to establish relationships between upwelling, marine productivity and the associated fisheries along the East African coast, given the changing global climate. Coastal upwelling is often associated with increased ocean productivity, with small pelagics frequently dominating species composition in coastal upwelling systems around the world (Plounevez and Champalbert, 2000). Small pelagic fishes are ecologically important because of their critical mid-trophic-level position, and their role in mediating the transfer of energy from lower to higher trophic levels, including to top predators (Cury *et al*., 2000).

The enhanced food environment which is associated with upwelling could have a positive impact on reproductive output through an increase in the quantity and/or quality of eggs produced during a spawning season, leading to increased population size (Brander *et al.*, 2016). Knowledge on feeding ecology is therefore necessary for an understanding of the fish stock and population dynamics. Such studies have been used to ascertain factors controlling the abundance and distribution of organisms, as well as providing information on positioning the fish in the food web of their environment (Post *et al.*, 2000). Moreover, the quality and quantity of food are among the most important exogenous factors directly affecting growth, and indirectly, maturation and mortality, of fish, thus being ultimately related to fitness (Wootton, 1990). The spatial and seasonal fluctuations in abundance of the organisms that constitute the food of a species have been evaluated and found to affect and influence biological activities of fishes (Kumar, 2015).

Trophically-mediated impacts of climate change are among the factors which are likely to affect the productivity of marine ecosystems and the composition of their lower trophic levels, particularly the phytoplankton (Brander *et al.*, 2016; Fuchs and Franks, 2010). Changes in phytoplankton composition will ultimately result in changes in the zooplankton community which is the primary food for anchovies and other small pelagic fishes (Ainsworth *et al.*, 2011; Blanchard *et al.*, 2012). Since food type or quantity influences spawning, fecundity, juvenile survival and consequent recruitment to the fishery, understanding the food and feeding habits of small pelagic is an important step in elucidating ecosystem dynamics and responses of fish stocks to climate change perturbations. Knowledge of the food and feeding behaviour patterns is also crucial for understanding the predicted changes that can result from any natural perturbations or anthropogenic interventions (Hajisamae *et al.*, 2006). Moreover, different sizes of fish belonging to the same species may have similar diets; however, they tend to choose or prefer particular dietary items depending on size and availability, among other factors (Sululu *et al.*, 2017). Dietary preferences among individuals of the same species may occur due to factors such as progressive increase in jaw morphology as the fish grows, and differences in locomotory abilities (Sudheesan *et al.*, 2009).

Studies on the food and feeding habits of small pelagic fishes have been reported globally (e.g. Hirota *et al.*, 2003, 2004). Only a few such studies have been carried out in Tanzania (e.g. Kamukuru and Mgaya, 2004; Kimirei *et al.*, 2013; Sululu *et al.*, 2017) and relatively few of these studies address the relationship between feeding habits, marine productivity and upwelling under a changing climate. It is essential to obtain knowledge of the food requirements, feeding behaviour patterns, and predator-prey relationships in order to understand the changes that can result from any natural or anthropogenic intervention (Hajisamae *et al.*, 2006). Therefore, this study was conducted to contribute to achieving the main objective of PEACC project, which was to investigate the responses of biological productivity and fisheries to changes in atmospheric and oceanographic conditions in the upwelling region associated with the East African Coastal Current. The study examined the food and feeding habits of the two most dominant small pelagic fishes, the Indian mackerel (*Rastrelliger kanagurta*) and the anchovy (*Stolephorus commersonnii*) in the coastal waters of Tanga region in Tanzania.

## Materials and methods

### Study area

The focus of this study was on two administrative districts in Tanga region (Tanzania), namely Mkinga and Tanga City. The selection of the study area was due to its proximity to the East African coastal current region. Fish sampling was conducted at Vyeru landing site for Mkinga district and Sahare landing site for Tanga City (Fig. 1). Selection of the two landing sites was based on the information that was acquired from catch assessment survey reports which indicated that there was a large number of active ring-net fishers who target small pelagic fish species and land their catches at these sites.

were those with relatively high productivity and were vulnerable to fisheries because they are fished heavily by artisanal fishers using ring-nets. For the purpose of this study, two types of samples were taken from two boats each month. The samples from the first boat was dominated with *S. commersonnii* (Engraulidae) individuals, while those from the second boat consisted of several small pelagic fish

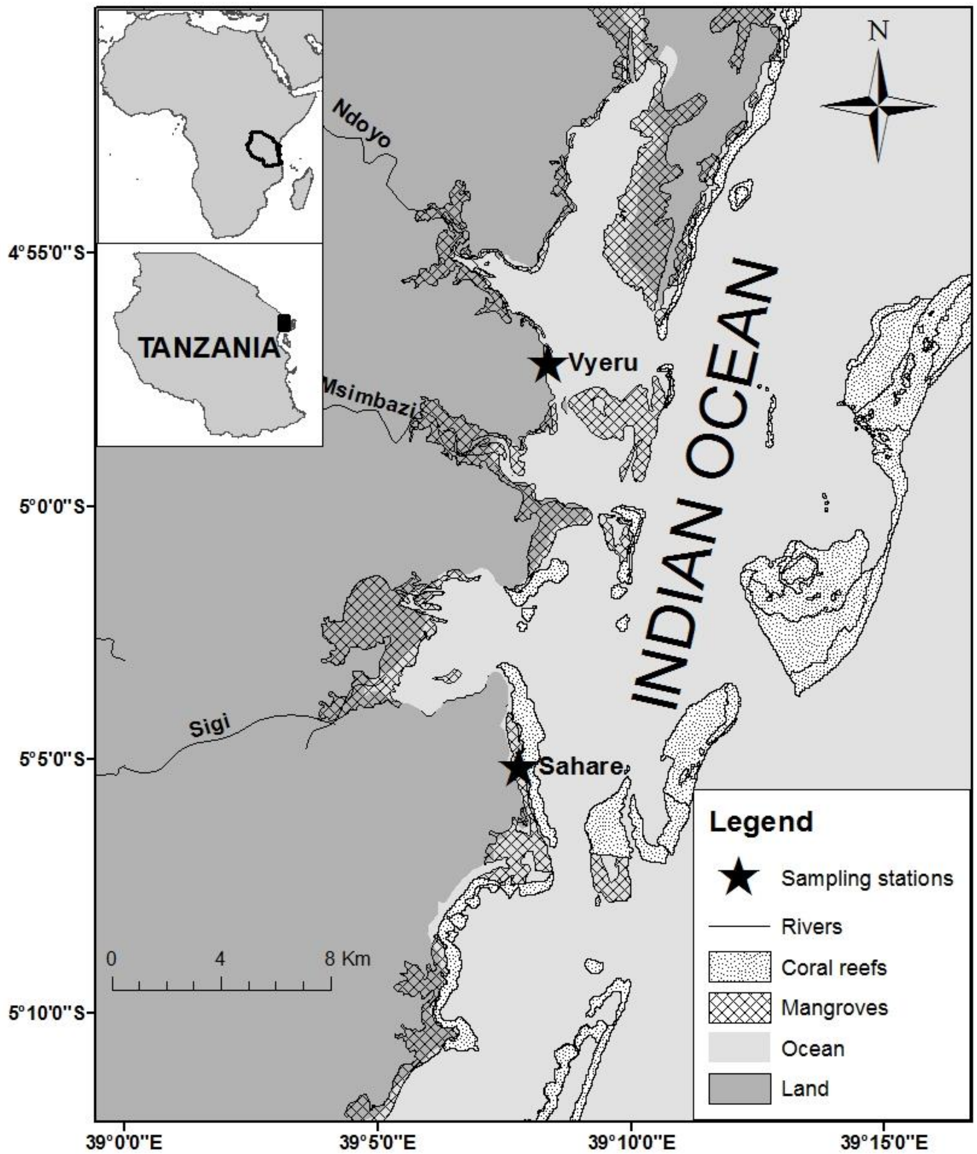


**Figure 1.** Sampling stations in two administrative districts, Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

### Fish Sampling

Fish specimens were collected on a monthly basis from July 2016 to June 2017. Sampling was conducted for two days each month; one day for each landing site. Samples of small pelagic fishes were randomly selected from the artisanal fishers. Priority species

species dominated by *R. kanagurta* (Scombridae). Both samples were immediately fixed in 10% formalin for analysis in the laboratory. All species encountered in the sample were dissected, but at the end of the field work, two species were chosen due to their dominance in the sample, but also due to their

**Table 1.** Class intervals and their frequency of *S. commersonnii* and *R. kanagurta* from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

| *Rastrelliger kanagurta* | | *Stolephorus commersonnii* | |
|---|---|---|---|
| **Class interval** | **Frequency** | **Class interval** | **Frequency** |
| 60-70 | 4 | 55-60 | 5 |
| 70-80 | 8 | 60-65 | 6 |
| 80-90 | 27 | 65-70 | 26 |
| 90-100 | 52 | 70-75 | 88 |
| 100-110 | 41 | 75-80 | 216 |
| 110-120 | 33 | 80-85 | 205 |
| 120-130 | 36 | 85-90 | 137 |
| 130-140 | 30 | 90-95 | 38 |
| 140-150 | 27 | 95-100 | 10 |
| 150-160 | 13 | | |
| 160-170 | 5 | | |
| 170-180 | 7 | | |
| 180-190 | 3 | | |
| 190-200 | 3 | | |
| 200-210 | 4 | | |

availability nearly throughout the year. Species which were less common in the sample and which were not available throughout most of the year were used for the species composition study.

### Gut content processing

Individuals of each species were measured for total length (TL) to the nearest mm, and weighed for total weight (TW) to the nearest 0.01 g. The stomachs were removed, cut open with surgical scissors, and the gut contents taken out using forceps and poured into a clean petri dish. Care was taken to separate the gut contents from the epithelial layer of the stomach lining to which they were closely adhering. The examination of gut contents was performed macroscopically or under a low power binocular microscope at 20 X magnification. Prey items were identified using Newell and Newell (1963). Identifiable prey were also grouped into two categories, namely large (penaeid shrimps, fish and fish larvae, squids, mantis shrimps and polychaetas), and small (mainly planktonic stages of penaeidae shrimps, Euphausiids, copepods, planktonic stage of gastropods, and phytoplankton) items. The fullness of the stomachs was classified as full, ¾ full, ½ full, ¼ full, or empty. Specimens with empty and ¼ full stomachs were considered to have fed poorly, followed by moderate (½ full) and actively fed (¾ and full). Proportions of food items in each stomach were estimated by eye as relative volumetric quantity, where the maximum volume of stomach contents was set at 100% and the food items found in each stomach were estimated as a volumetric percentage of the total stomach volume (Hyslop, 1980). The gravimetric method was not used due to possible errors associated with weighing small prey items from small fish whose stomachs also contained water. Numerical estimates were not used because they overemphasize the importance of small prey items taken in large numbers (Hyslop, 1980). To assess changes in the diet with fish size, *S. commersonnii* were assigned into eight length classes from 60-65 mm to 95-100 mm TL, and *R. kanagurta* into thirteen classes from 80-90 mm to 200-210 mm TL (Table 1). The volumetric proportions of the main prey categories were then computed per fish size class.

## Results

A total of 1434 stomachs of *S. commersonnii* and 320 stomachs of *R. kanagurta* were examined (Table 1). 51.4% of *S. commersonnii* examined had food in their stomachs while 48.6 % had empty stomachs. 73.1% of *R. kanagurta* individuals had food in their stomachs and 26.9% had empty stomachs.

**Table 2.** Number of *S. commersonnii* and *R. kanagurta* dissected during the study period from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

| Months-year | *S. commersonnii* | *R. kanagurta* |
|---|---|---|
| Jul-17 | 164 | 46 |
| Aug-17 | 150 | 48 |
| Sep-17 | 100 | 19 |
| Oct-17 | 100 | 18 |
| Nov-17 | 100 | 34 |
| Dec-17 | 150 | 29 |
| Jan-18 | 100 | 23 |
| Feb-18 | 150 | 58 |
| Mar-18 | 120 | 0 |
| Apr-18 | 100 | 20 |
| May-18 | 100 | 0 |
| Jun-18 | 100 | 25 |
| **Total** | **1434** | **320** |

## Diet composition

Planktonic stages of penaeid shrimps made up the bulk of the diet of *S. commersonnii*, followed by fish larvae and zooplankton. (Fig. 2a). Other minor food items which were recorded included phytoplankton (predominantly the diatoms *Nitzschia* spp and *Flagillaria* spp), fish scales, insect larvae and debris. In contrast, *R. kanagurta* fed predominantly on fish, particularly *S. commersonnii*, together with juvenile stages of other fish species. Sub-adult penaeid shrimps were the second most important food item followed by zooplankton (Fig. 2b). Other minor food items in the stomachs of *R. kanagurta* included mantis shrimps (Stomatopoda), juvenile squids (Cephalopoda), and polychaetes (Polychaeta).

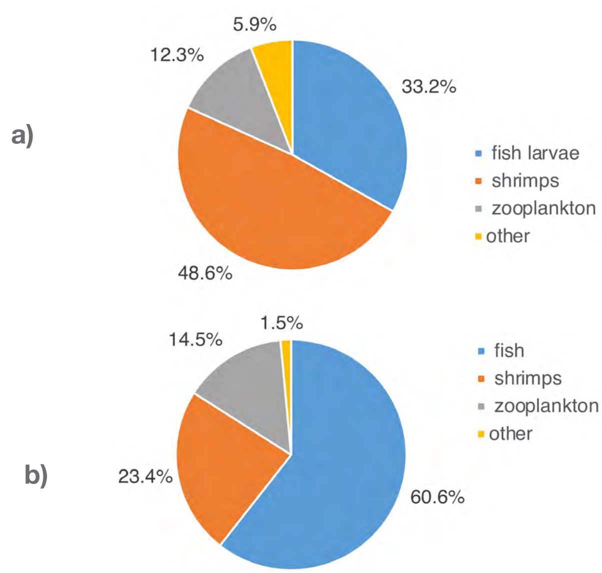


**Figure 2.** Percentage diet composition of (a) *S. commersonnii* and (b) *Rastrelliger kanagurta* from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

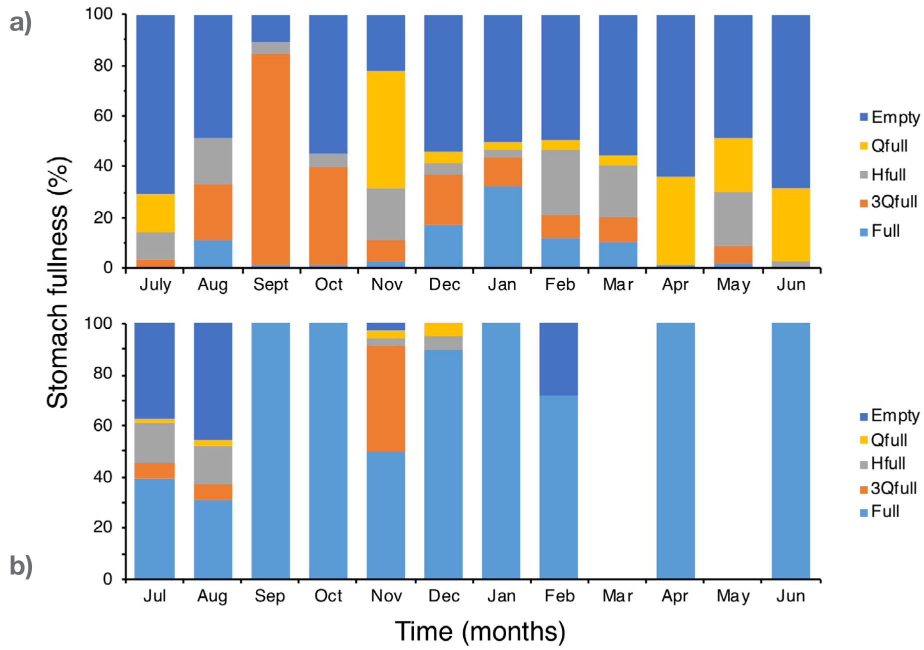


**Figure 3.** Seasonal variation in feeding intensity of (a) *S. commersonnii* and (b) *R. kanagurta* from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

## Seasonal variation in feeding intensity

Seasonal variation in feeding intensity of *S. commersonnii* and *R. kanagurta* is shown in Fig. 3a and 3b, respectively. *R. kanagurta* was a more active feeder compared to *S. commersonnii*, having individuals with 100 % full stomachs in the months of September, October, January, April and June, and empty stomachs in August, July, and February, and a small number in November (Fig. 3b). Conversely, *S. commersonnii* fed far less actively, with full stomachs seldom being recorded.

## Seasonal variation in diet composition

Fish, particularly *S. commersonnii*, formed the main prey item of *R. kanagurta*, particularly in March, November and February, with penaeid shrimps contributing substantially in January and October (Fig. 4b).

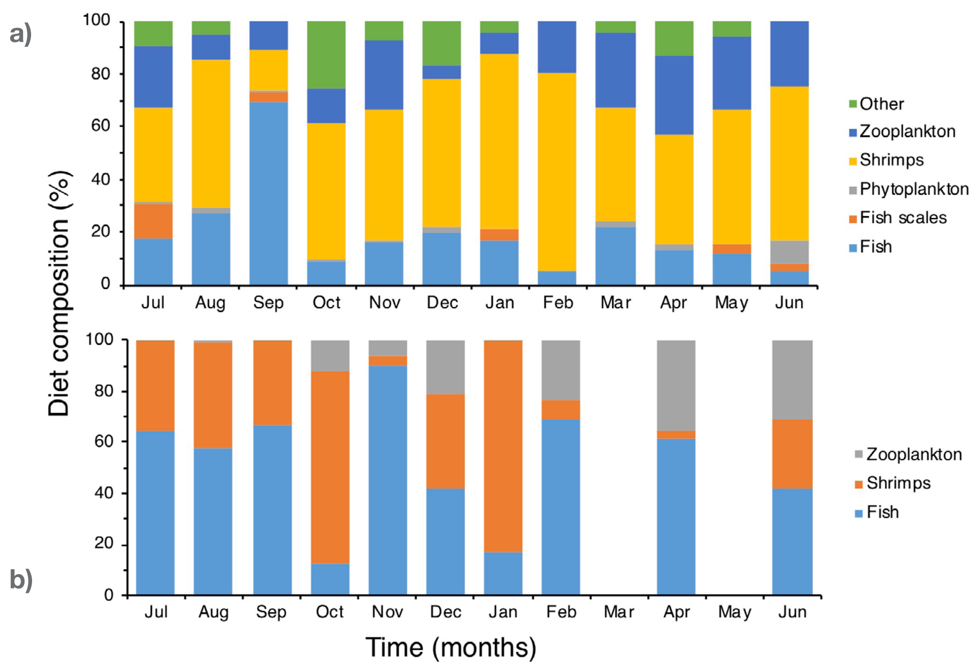


**Figure 4.** Seasonal variation in diet composition of (%) of (a) *S. commersonnii* and (b) *R. kanagurta* from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

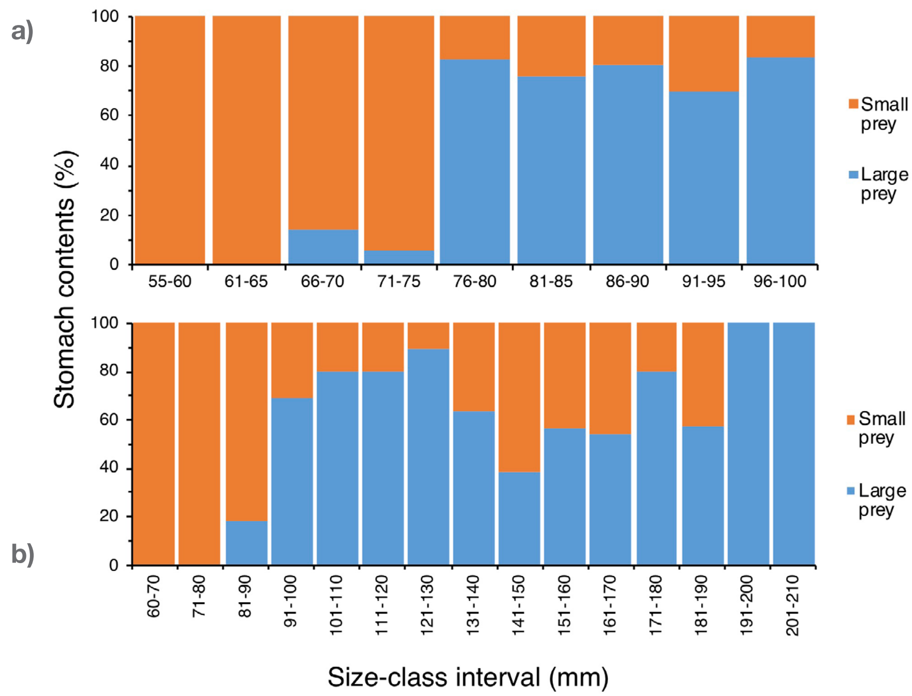


**Figure 5.** Ontogenic diet shift in (a) *S. commersonnii* and (b) *R. kanagurta* from Sahare in Tanga City and Vyeru in Mkinga district, Tanzania.

Penaeid shrimps were the main prey of *S. commersonnii* throughout the study period (particularly in March, May and December), except in September and November when fish larvae dominated (Fig. 4a). Zooplankton were generally present in the diet of *S. commersonnii* in small fractions, except in March and May (Fig. 4a).

### Ontogenic Diet shift

The importance of large prey items increased with increasing fish length in both species (Fig. 5). *S. commersonnii* up to 65 mm TL fed exclusively on small prey items, mainly zooplankton (copepods), phytoplankton (diatoms), and early planktonic stages of penaeid shrimps (mysis and protozoea). At sizes >65 mm, they started to feed on large prey (Fig. 5a), mainly postlarvae and juvenile stages of penaeid shrimps. However, the proportion of large prey items was higher in fish sizes ≥75 mm (Fig. 5a). These were mostly juvenile penaeid shrimps, some polychaetes and fish larvae. Juvenile stages of *S. commersonnii* and fish scales were occasionally found in the stomachs of *S. commersonnii*. Likewise, *R. kanagurta* of sizes ≤ 75 mm only fed on small prey items (Fig. 5b), mainly post-larval stages of penaeid shrimps and zooplankton. At sizes ≥80 mm, this species was already feeding on large prey items, which consisted of juvenile fish and post-larval stages of penaeid shrimps. However, small prey items still appeared in its diet (Fig. 5b). At sizes ≥ 210 mm, the species fed entirely on large prey items (Fig. 5b), which consisted of juvenile penaeid shrimps, juvenile stages of fish other than *S. commersonnii*, and subadult and adult stages of *S. commersonnii.*

## Discussion

The present study shows that planktonic stages of penaeid shrimps constituted the main diet of *S. commersonnii*, followed by fish larvae. Zooplankton, especially copepods and crustacean larvae, as well as phytoplankton and fish scales represented minor prey items. This suggests that *S. commersonnii* has two modes of feeding; that is, filter feeding on small food items such as plankton, and particulate feeding on large items such as the planktonic stages of penaeid shrimps (James and Findlay, 1989), which could be the main feeding mode in this species. The results of this study show close similarities with earlier observations from Indian waters by Kumar (2015) who found that planktonic copepods and planktonic crustaceans constituted the core diet of *S. commersonnii*. Studies carried out in Indian waters have indicated that other Engraulid species, in the same family as *S. commersonnii,* have been found to derive the bulk of their carbon from larger zooplankton (van der Lingen *et al.*, 2006).

The diet composition data showed that *R. kanagurta* fed primarily on *S. commersonnii* and penaeid shrimps suggesting that the species is carnivorous. The fishes found in the guts of this species were too large to be caught in the filter feeding apparatus. Additionally, *R. kanagurta* have sharp teeth to facilitate the active capture of prey, which supports the observed dominance of fish in its diet. This finding is contrary to earlier reports that the species is a plankton feeder (Bagheri *et al.,* 2013; Noble, 1965). Pradhan (1956) found neither fish larvae nor vertebrate material in the stomach of *R. kanagurta* and concluded that the species was an exclusive plankton feeder, alternating between zooplankton and phytoplankton in different seasons. The presence of fish in the diet of *R. kanagurta* has also been reported by Sivadas and Bhaskaran (2009) who recorded two to five fish (*Bregmaceros* sp) in each stomach. This supports the contention from this study that the predominance of fishes in the stomachs of sampled *R. kanagurta* was not a result of accidental consumption.

The differences which were observed in the feeding habits of *R. kanagurta* compared to findings from other studies is likely related to availability of food in the area where they were caught, since diet of a fish may change due to extrinsic factors such as biotope or region (Sivadas and Bhaskaran, 2009; Osman *et al*., 2013). Moreover, the methodology used in the other studies to assess prey was different from the present study which might also account for the observed differences. In addition, Hashem *et al.* (1982) stated that the feeding habits of different species, and also within the same species, may appear to vary in catches caught with different fishing methods. In their study they found that fish (*Sardinella aurita* and *Sardinella maderensis*) caught by purse-seine fed particularly on zooplankton, while those that were caught by gill net and beach seine were filter feeders. This could be due to the fact that beach seines are operated in shallow water, where the available food may differ from that of deep/pelagic water where gears like purse seines are operated. The method and gear which was used to catch *R. kanagurta* (using artificial light) in the present study was designed to attract *S. commersonnii*, so it is likely that the predator was feeding on this prey item prior to capture resulting in the observed dominance of *S. commersonnii in R. kanagurta* stomachs.

*S. commersonnii* fed actively in December, January, September and October. This can be attributed to the high abundance of the preferred food items in those months, or because more energy is needed during the spawning season (Farrag, 2010; Osman *et al*., 2013). The reproductive biology of *S. commersonnii* indicates that spawning occurs throughout the year, but with peaks in October and January (Sululu *et al*., this issue), which agrees well with this assumption. However, the present study reports higher numbers of empty stomachs in *S commersonnii* during the study period, perhaps attributable to a low density of preferred food items in the habitat. These findings agree with other studies such as Manojkumar *et al.* (2015, 2016) who found a predominance of empty stomachs throughout the season and associated this condition with the non-availability of preferred food items during certain months.

Some empty stomachs sampled during the present study appeared shrunken and contained mucous, while others were expanded, but contained no food items. The latter condition is believed to occur in fish which have recently regurgitated food (Madkour, 2012); which could be the case in the present study. Conversely, *R. kanagurta* fed actively throughout the study period, except in July, August, November and December. Generally, the main food item for *R. kanarguta* was available in the environment throughout the study period, which might explain this observation.

Both *S. commersonnii* and *R. kanagurta* exhibited significant ontogenetic variations/shifts in prey items. At early stages, both *S. commersonnii* and *R. kanagurta* fed exclusively on small prey items and shifted to feeding on large prey items with increasing fish size, which may be an adaptation to reduce intra-specific competition among different size groups (Osman *et al*., 2013). On the other hand, ontogenic diet shift has been attributed to factors such as age-specific changes in the use of habitat (Kamukuru and Mgaya, 2004; Kimirei *et al*., 2013). In the present study, both small and large fish of both species were caught in the same habitat indicating that ontogenic diet shift may be related to a difference in energy requirements according to different developmental stages (Madkour, 2012). Larger fish have different diet requirements to smaller individuals and attempt to satisfy their needs by consuming a more extensive variety of prey (Kumar *et al.*, 2015). Changes in the mouth gape and improvement in swimming ability as the fish grows also result in ontogenic diet shifts. A small mouth limits the size of prey items that can be ingested (Kumar *et al*., 2015), and improved locomotory ability and visual detection can allow larger fish to shift to large prey items (Kahilainen, 2004; Wooton, 1998).

## Conclusion

The food and feeding habits of *S. commersonnii* and *R. kanagurta* were studied and the results indicated that *S. commersonnii* has two modes of feeding; filter feeding on small food items, and particulate feeding on large particles such as the planktonic stages of penaeid shrimps, suggesting that the species is a planktivorous carnivore. The study also revealed that *R. kanagurta* is a carnivore in the geographic area studied, contrary to previous studies which characterised it as a plankton feeder. Productivity studies have found that increasing temperature has a negative influence on Chl-a concentration (primary productivity). Changes in productivity that results in a changes of zooplankton abundance will likely have an impact on the population of *S. commersonnii* and other species which feed on zooplankton. This study presents results of stomach analysis, which may not show a complete picture of the feeding dynamics of the species. Results from a zooplankton study which was conducted as part of the PEACC project after realising that this would contribute to the understanding of the feeding dynamics of the studied fish species will enhance knowledge of food availability, especially for *S. commersonnii* and other zooplankton feeders.

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## References

Ainsworth CH, Samhouri JF, Busch DS, Cheung WWL, Dunne J, Okey TA (2011) Potential impacts of climate change on North-east Pacific marine food webs and fisheries. *ICES Journal of Marine Science* 68 (6, 1): 1217-1229

Bagheri A, Sadeghi MS, Daghooghi B (2013) Feeding biology of Indian Mackerel (*Rastrelliger kanagurta*) in Hormozgan Province waters (Persian Gulf). Journal of Marine Biology 5: 35-46

Blanchard JL, Jennings S, Holmes R, Harle J, Merino G, Allen JI, Barange M (2012) Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society B: Biological Sciences 367 (1605): 2979-2989

Bodiguel C, Breuil C (2015) Report of the meeting on the small marine pelagic fishery in the United Republic of Tanzania. Report/Rapport: SFFAO/ 2015/34. August/ Août 2015. IOC-SmartFish Programme of the Indian Ocean Commission. FAO. Ebene, Mauritius. 90 pp

Brander K, Ottersen, G, Bakker JP, Beaugrand G, Herr H, Garthe, S, Tulp I (2016) Environmental Impacts—Marine Ecosystems. In: Quante M, Colijn F (eds) North Sea region climate change assessment, Chapter 8, pp. 241-274). Springer (Regional climate studies) [doi: 10.1007/978-3-319-39745-0_8]

Cury P, Bakun A, Crawford RJM, Jarre-Teichmann A, Quiñones RA, Shannon LJ, Verheye HM (2000) Small pelagics in upwelling systems: patterns of interaction and structural changes in "waspwaist" ecosystems. ICES Journal of Marine Science 57: 603-61

Farrag MMS (2010) Fishery biology of Red Sea immigrant *Etrumeus teres* (Family: Clupeidae) in the Egyptian Mediterranean water, off Alexandria. MSc Thesis, Zoology Department, Faculty of Science, Al-Azhar University (Assuit), Egypt

Fuchs HL, Franks PJS (2010) Plankton community properties determined by nutrients and size-selective feeding. Marine Ecology Progress Series 413: 1-15

Hajisamae S, Yeesin P, Ibrahim S (2006) Feeding ecology of two sillaginid fishes and trophic interrelations with other co-existing species in the southern part of South China Sea. Environmental Biology of Fishes 76: 167-176

Hashim M, Wassef M, Faltas M (1982). Food and feeding habits of Sardines and their effects on the condition of fish captured by different fishing methods. Bulletin of National Institute of Oceanography and Fisheries 8: 229-238

Hirota Y, Honda H, Ichikawa, T Mitani T (2003) Stomach contents of round herring *Etrumeus teres* in Tosa Bay. Fisheries Biology and Oceanography, Kuroshio 4: 35-44

Hyslop EJ (1980) Stomach contents analysis – a review of methods and their application. Fish Biology 17: 411-429

James AG., Findlay KP (1989) Effect of particle size and concentration on feeding behaviour, selectivity and rates of food ingestion by the Cape anchovy *Engraulis capensis*. Marine Ecology Progress Series 50: 275-294

Kahilainen K (2004) Ecology of sympatric whitefish (*Coregonus lavaretus* (L.)) forms in a subarctic lake. PhD dissertation, University of Helsinki, Helsinki, Finland. 44 pp

Kamukuru AT, Mgaya YD (2004) The food and feeding habits of blackspot snapper *Lutjanus fluviflamma* (Pisces: Lutijanidae) in shallow waters of Mafia Island, Tanzania. African Journal of Ecology 42: 49-58

Kimirei IA, Nagelkerken I, Trommelen M, Blankers P, van Hoytema N, Hoeijmakers D, Huijbers CM, Mgaya YD, Rypel AL (2013) What drives ontogenetic niche shifts of fishes in coral reef ecosystems? Ecosystems 16: 783-796

Kumar MA, Padmavati G, Venu S (2015) Food and feeding dynamics of *Stolephorus commersonnii* (Lacepede, 1803) (Family: Engraulidae) from South Andaman. Marine Biology, Article ID 870919. 8 pp

Manojkumar PP, Pavithran PP, Ramachandran NP (2015) Food and feeding habits of *Nemipterus japonicus* (Bloch) from Malabar coast, Kerala P. Indian Journal of Fisheries 62: 64-69

Manojkumar P P, Pavithran PP (2016). Diet and feeding habits of *Saurida tumbil* (Bloch, 1795) from northern Kerala, south-west coast of India. Indian Journal of Fisheries 63: 41-47

Madkour FF (2012) Feeding ecology of the round sardinella, *Sardinella aurita* (family: clupeidae) in the Egyptian Mediterranean waters. International Journal of Environmental Science and Engineering 2: 83-92

Newell GE and Newell RC (1963) Marine plankton, a practical guide. Hutchinson Educational Ltd., London. 207 pp

Noble A (1965) The food and feeding habit of the Indian mackerel *Rastrelliger kanagurta* (Cuvier) at Karwar. Indian Journal of Fisheries 9A: 701-713

Osman AGM, Farrag MMS, Akel EHK, Moustafa MA (2013) Feeding behavior of lessepsian fish *Etrumeus teres* (Dekay, 1842) from the Mediterranean Waters, Egypt. Egyptian Journal of Aquatic Research 39: 275-282

Plounevez S, Champalbert G (2000) Diet, feeding behaviour and trophic activity of the anchovy (*Engraulis encrasicolus* L.) in the Gulf of Lions (Mediterranean Sea). Oceanologica Acta 23: 175-192

Post D, Conners M, Goldberg D (2000) Prey preference by a top predator and stability of linked food chains. Journal of Ecology 81: 8-14

Pradhan LB (1956) Mackerel fishery of Karwar. Indian Journal of Fisheries 3: 141-185

Raab K, Nagelkerke LAJ, Boerée C, Rijnsdorp AD, Temming A, Dickey-Collas M (2011) Anchovy *Engraulis encrasicolus* diet in the North and Baltic Seas. Journal of Sea Research 65: 131-140

Sivadas M, Bhaskaran M (2009) Stomach content analysis of the Indian mackerel *Rastrelliger kanagurta* (Cuvier) from Calicut, Kerala. Indian Journal of Fisheries 56: 143-146

Sudheesan D, Jaiswar AK, Chakraborty SK, Pazhayamadom DG (2009) Predatory diversity of finfish species inhabiting the same ecological niche. Indian Journal of Fisheries 56: 169-175

Sululu JS, Ndaro SN, Kangwe S J (2017) Food and feeding habits of the Delagoa threadfin bream, *Nimepterus bipunctatus* (Valenciennes 1830) from the coastal waters around Dar es Salaam, Tanzania. Western Indian Ocean Journal of Marine Science 16: 13-23

Van der Lingen CD, Hutchings L, Field G (2006) Comparative trophodynamics of

Anchovy *Engraulis encrasicolus* and sardine *Sardinops sagax* in the southern Benguela: are species alternations between small pelagic fish trophodynamically mediated? African Journal of Marine Science 28: 465-477

Wootton R J (1990) Ecology of teleost fishes. Chapman and Hall, London. 404 pp

# Reproductive biology of the anchovy (*Stolephorus commersonnii*, Lacepède, 1803) and spotted sardine (*Amblygaster sirm*, Walbaum, 1792) from Tanga Region, Tanzania

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## Abstract

The present study investigated the reproductive biology of *Stolephorus commersonnii* and *Amblygaster sirm* at two landing sites in Tanga on the northern coast of Tanzania. Fish samples were collected on a monthly basis from ringnets operated by artisanal fishers in the nearby coastal waters. Spawning seasons were determined using gonadosomatic index (GSI) and gonadal maturity stages. The size at first maturity was 57.7 mm and 66.2 mm total length for male and female *S. commersonnii* respectively. Male and female *A. sirm* were estimated to attain first maturity at 147.7 mm and 169.2 mm respectively. The spawning seasons of both species were protracted. *S. commersonnii* demonstrated a year round spawning cycle with peaks in August, October and January. The peak spawning season for male and female *A. sirm* was recorded in August and September respectively. Both species exhibited skewed size-dependent sex ratios with females predominating in the larger size classes. *A. sirm* had a higher fecundity rate with a maximum of 96,500 eggs in the largest female fish of 258 mm as compared to *S. commersonnii* (10,055 eggs) in the largest fish of 98 mm. The mean (±SE) total fecundity of *S. comersonnii* and *A. sirm* was 5,134.7 ± 136.9 eggs, and 47,029.03 ± 1,435.13 eggs in females of sizes 68 mm to 98 mm and 170 mm to 258 mm respectively.

**Keywords:** Anchovies, Clupeids, Reproduction, Tanga, Ringnet fishery

## Introduction

Studies on the reproductive biology of fishes provide essential knowledge for stock management and conservation (King and McFarlane, 2003; Silva *et al.*, 2005). Most studies on fish reproduction rely on the classification of gonad maturity stages, which are critical for the accurate determination of the reproductive strategy of a species (Franco *et al.*, 2014). However, the gonadosomatic index (GSI) is used as an indicator for the sexual cycle of different fish species, through which spawning seasons can be determined (Nunes *et al.*, 2011). Further, the knowledge on spawning season and fecundity of a certain fish species helps to manage and maintain the fishery for such species as well as facilitate fishing plan strategies (Azza, 1992). The success of any species is eventually determined by the ability to reproduce successfully in fluctuating environments in order to maintain the population (Veerappan *et al.*, 1997). Therefore, a comprehensive knowledge of the maturation cycle assists in predicting the annual changes that the fish population undergoes.

Landings of Engraulidae and Clupeidae occupy the second and third places worldwide, respectively

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(Zhang, 2001), providing the global human population with abundant and high-quality animal protein. The engraulid fishes, commonly known as anchovies, are widely distributed in both tropical and sub-tropical waters (Mcgowan and Berry, 1983). Clupeids are also widely distributed with about 65 genera and 214 species worldwide already confirmed (Meng *et al.*, 1995). Most engraulids, including *S. commersonnii*, spawn in coastal areas on the inner continental shelf and their recruitment frequently takes place in protected shallow areas that offer sufficient food and shelter from predators (Silva *et al.*, 2003).

Individuals of the anchovy, *S. commersonnii* Lacépède, 1803 (Engraulidae) are distributed globally from 27°N to 24°S and from 38°E to 155°E in waters with a depth of less than 50 m (Gao *et al.*, 2016). Many species of anchovies are economically important in several regions (Franco *et al.,* 2014); essentially, they are utilized throughout the tropical Indo-Pacific region for human consumption and as tuna bait (Andamari *et al.*, 2002). Moreover, anchovies are known to form a vital part of marine food chains and form a link between the planktonic organisms and the predators such as carnivorous fishes, marine mammals, and birds. On the other hand, the clupeid *A. sirm* is more abundant in the Western Indian Ocean (WIO), South China Sea and in coastal waters of Papua New Guinea, Australia (Fischer and Bianchi, 1984), Indonesia, Philippines and Thailand (Chullarson and Martosubroto, 1986). The demand for *A. sirm* in the coastal states of the Indian Ocean is not only as a food fish, but also as a bait fish for the handline and longline fishery (Pradeep *et al.*, 2014). Most clupeids and engraulids are reported to be multiple spawners, releasing many batches of eggs every year, hence producing batches of fecundity (Alheit, 1989). Some of the engraulids spawn batches of eggs every 2 - 10 days (Clarke, 1987).

Apart from being ecologically important through linking of planktonic organisms and predator fishes, S. *commersonnii* and *A. sirm* are also essential economically to fishers and coastal communities in Tanzania. Currently these species are in high demand in and out of the country as a human protein source and as animal food. Despite the ecological and economic significance of *S. commersonnii* and *A. sirm*, there is a paucity of information on the reproductive biology of these species from Tanzania and most of the WIO countries. However, a few reproductive biology studies have been reported in Tanzania for other non-small pelagic species (Kamukuru, 2009; Kamukuru and Mgaya, 2004; Lamtane *et al.*, 2007). The present study therefore examined the reproductive activity of *S. commersonnii* and *A. sirm* with the aim of establishing important biological information for conservation and management of these species.

## Materials and methods

### Study sites

The study was undertaken at two landing sites; namely, Sahare and Vyeru, which lie at 05⁰ 05' S, 039⁰ 07' E and 04⁰ 57' S, 039⁰ 08' E, respectively, in Tanga region in the northern part of Tanzania (Fig. 1). The criteria for choosing the two landing sites were based on their proximity to the East African Coastal Current (EACC) region in the Pemba Channel, and the associated upwelling, and their history within the small pelagic fishery, being one of the most productive areas for small pelagics in Tanzania

### Specimens and data collection

Specimens for the study were obtained from ringnets operated by artisanal fishers during dark moons for a period of one year, from August 2016 to July 2017. Specimens of both *S. commersonnii* and *A. sirm* were collected from different fishing units at the two landing sites. The availability of specimens relied entirely on the catch of fishermen, while the frequency of sampling was three days per lunar month. However, individuals of *A. sirm* were not sampled in April 2017 at Vyeru due to their absence in the catch. During sampling, individuals of both species were identified using the field guide key by (Fischer and Bianchi, 1984). Altogether, 3631 and 1159 specimens of *S. commersonnii* and *A. sirm* respectively were collected. Each specimen of the two species was measured for total length (TL) on a measuring board to the nearest millimetre (± 0.1 mm), body length (BL), body weight (TW) and gonad weight (GW) to the nearest gram (±0.01g) using a sensitive digital balance.

The sex of each specimen was determined by macroscopic examination of the gonads. The gonadal maturity stages of males and females were assigned macroscopically according to the description of Athukoorala *et al.* (2015) based on five stages. Basically, external morphological criteria (shape, colour of testis and ovaries) were used to assign sex and maturity stages upon dissection.

The spawning seasons were established based on the analysis of two aspects: (i) gonadal maturity stages;

and (ii) gonadosomatic index (GSI), which was determined as:

GSI = (Gonad weight/ total fresh weight of fish) ×100.

The length at first maturity ($L_{M50}$) was determined by computing the proportion of mature specimens in all size classes. Mature individuals at stage III and above were considered as mature for determination of $L_{M50}$ of these species. The length at which 50% of individuals were found to be mature was considered as the size the species reaches maturity for the first time. The $L_{M50}$ of both sexes was estimated at class intervals of 5 mm and 10 mm respectively and the data fitted into an ogive function; a non-linear regression as described by Duponchelle and Panfili (1998):

$$(L_{M50}) = \left( \%MF = \frac{1}{1 + e^{(-a(L - L_{M50}))}} \right)$$

where %MF represents percentage of mature fish by size class, and $L$ is the mid length of each size class, and $a$ and $L_{M50}$ are constants for the model. The proportion of the two sexes comparative to one another was used to determine the sex ratio of the two species. Fecundity was determined by taking a pair of ovaries from mature female individuals (stages III and IV) and preserving these in plastic bottles containing Gilson's

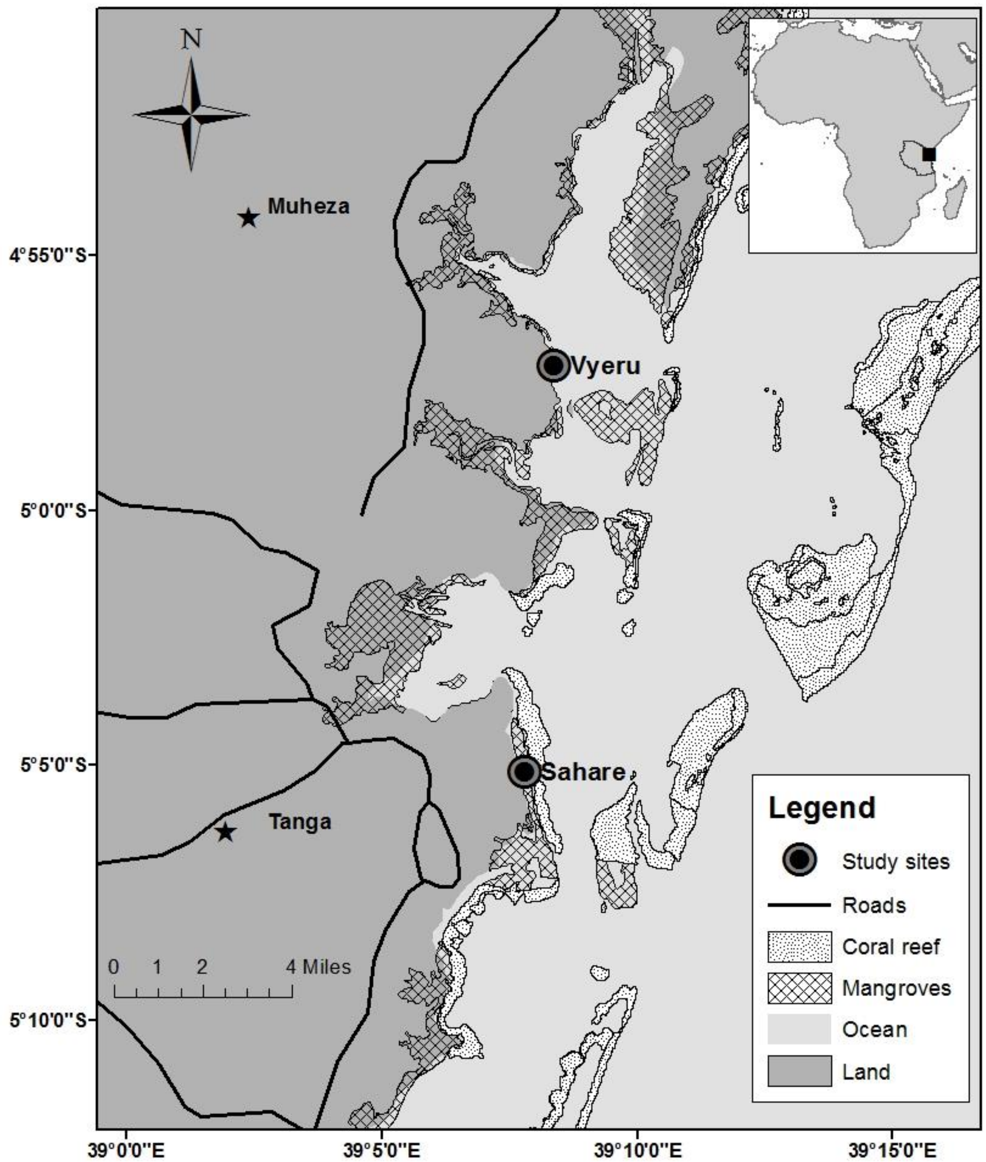


**Figure 1.** Location of sampling sites along the coast of Tanga Region.

fluid. The sample of ovaries in bottles were kept at room temperature for three months, but were frequently and vigorously agitated to facilitate release of the eggs from the ovarian tissues.

The fecundity was determined by counting mature yolked oocytes of a ripe and gravid fish. The total fecundity of females of the two species was determined using a volumetric method, whereby plastic bottles containing ova and Gilson's fluid were repeatedly filled with tap water, and then the supernatant and remains of ovarian tissues decanted. Cleaned ova of *S. commersonnii* and *A. sirm* were diluted with tap water at a volume of 500 and 1000 ml, respectively. The mixture of eggs and tap water was transferred into a plastic jar of 90 mm diameter and 103 mm height, and then a plastic ruler was used to stir the mixture until the eggs were seen to be evenly distributed. A 1 ml subsample of the mixture (eggs and water) was quickly taken from the sample in the jar and then counted under a dissecting microscope at X10 magnification. A total of five (5) subsamples were drawn per specimen, and the average from these subsample counts was considered as the number of ova in a mixture of specified volume (Murua *et al*, 2003). Total fecundity of each female of both species was estimated following the formula given by Holden and Raitt (1974) as follows:

$$F = nV/v$$

Where n = number of eggs in the subsample, V = volume to which the total number of eggs is made up, and v = volume of the subsample.

The relationship between size (length) and fecundity was derived from the equation:

$$Y = a + bL$$

where Y is fecundity, L is the total length of the fish in cm and *a* and *b* are constants as described by Madan and Velayudhan (1984).

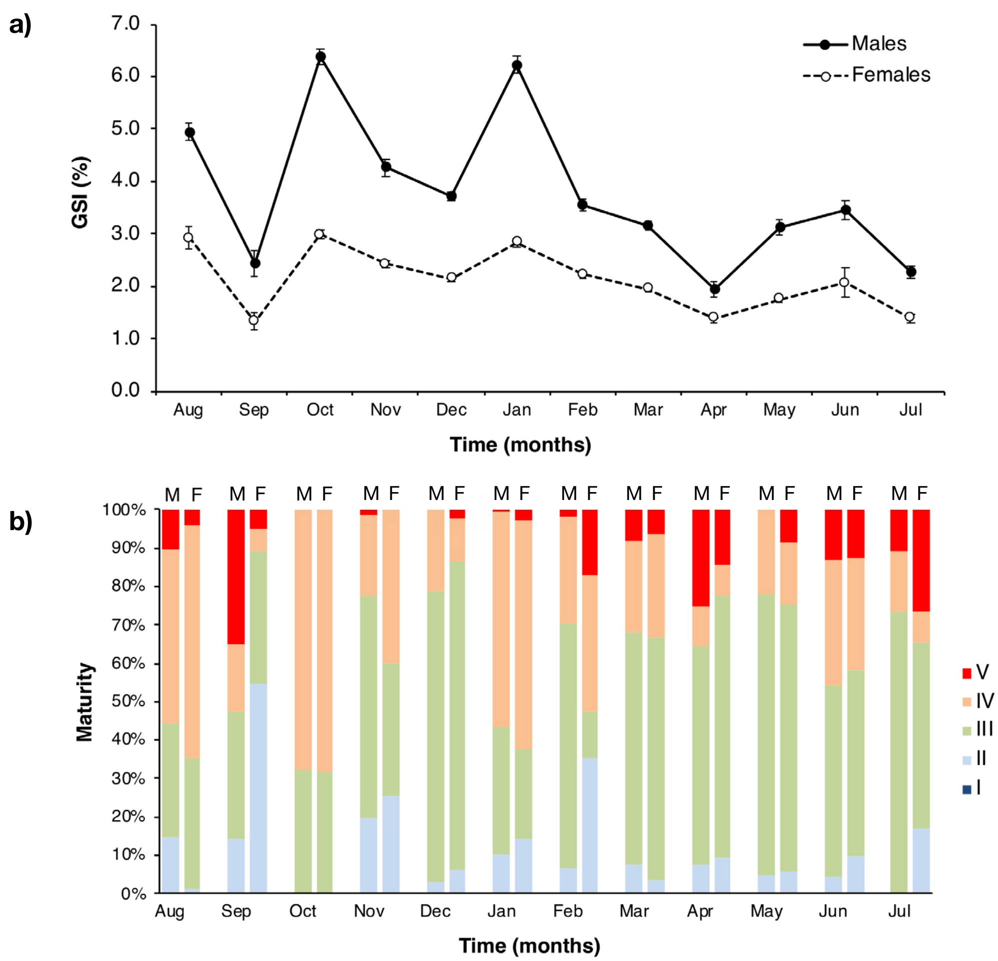


**Figure 2.** (a) Monthly variations in mean values (±SE) of gonadosomatic index (GSI), and (b) gonadal maturity stages of male (M) and female (F) *S. commersonii*.

## Data analysis

The variation in the sex ratio of *S. commersonnii* and *A. sirm* was tested using the Chi-square test. The differences in GSI and condition factor (k) between sexes were tested using an independent *t* test. One way ANOVA was also applied to test GSI differences among months, and Tukey's *post-hoc* test was used for significance analyses in GSI values to determine which months were different from each other. Linear regression analysis was used to test the correlation between total length of female mature individuals of both species and their fecundity. All statistical data analyses were performed using SPSS analytical software. A 0.05 significance level was used for all tests.

## Results

Mean monthly GSI values of *S. commersonnii* ranged from 1.93% to 6.38% in males and 1.34% to 3.00% in females, whereas in *A. sirm* they ranged from 0.25% to 2.68% and from 0.27% to 3.19% respectively (Fig. 2a & 3a). Findings of this study revealed that spawning in both species is protracted. More importantly, it was observed that *S. commersonnii* spawned throughout the year, as gravid gonads (capable spawning individuals in stage IV) of this species were observed during all months.

The highest GSI values and percentages of gravid gonads of both sexes of *S. commersonnii* were recorded in October and January with females extending to August indicating peak spawning during these months (Fig. 2a & b). In *A. sirm*, spawning occurred between August and July for males and between September and July for females. The highest GSI values of male and female *A. sirm* in August and September respectively corresponded to higher proportions of individuals with ripe gonads (Stages IV) signifying that peak spawning occurs within these months (Fig. 3 a & b).

One-way ANOVA revealed that GSI values varied significantly among months in both species, with $F_{(11, 1727)} = 81.2$; $P< 0.001$ and $F_{(11, 1416)} = 22.2$; $P<0.001$ in males and females of *S. commersonnii* respectively.

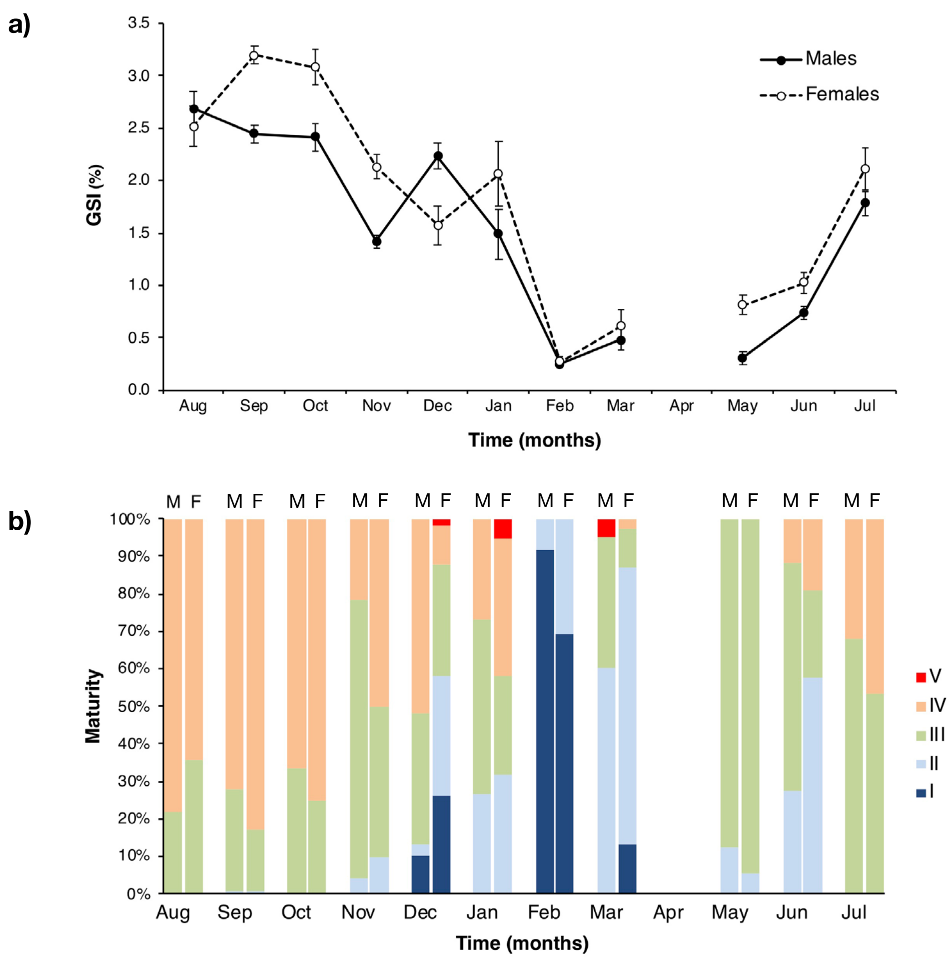


**Figure 3.** (a) Monthly variations in mean values (±SE) of gonadosomatic index (GSI), and (b) gonadal maturity stages of male (M) and female (F) *A. sirm*.

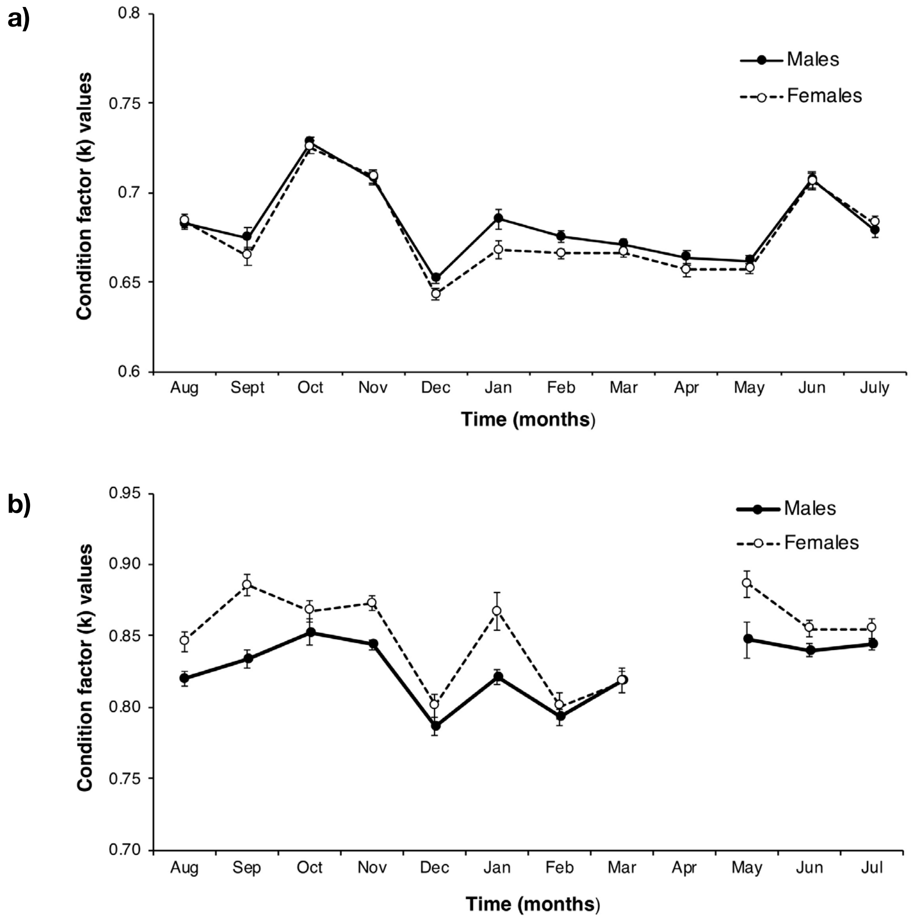


**Figure 4.** Monthly variations in the condition factor (K) of (a) *S. commersonnii*, and (b) *A. sirm* from both Sahare and Vyeru sites.

In *A. sirm* the GSI values were found to be $F_{(9, 398)} = 39.5$; $P<0.001$ for males and $F_{(10, 484)} = 41.8$; $P < 0.001$ for females. The GSI values in peak spawning months of males (October and January) and females (August, October and January) of *S. commersonnii* were significantly higher compared to other months (Tukey *post- hoc* test, $P < 0.001$). On the other hand, the peak GSI values of male and female *A. sirm* during August and September were significantly higher than all other months, with the exception of August and December (Tukey *post-hoc* test, $P = 0.000$). The GSI showed significant difference between sexes in both *S. commersonnii* (*t* test, t =26.3, $P < 0.001$) and *A. sirm* (*t* test, t = - 3.7, $P < 0.001$).

## Condition factor

The monthly condition factor (K) for *S. commersonnii* revealed similar high values in both males and females between October (0.73) and November (0.71) respectively. This was followed by a decline through to December, an increase through to January and then a decline from February to May and picked again in June in both sexes (Fig. 4a). The monthly K values for both males and females of *A. sirm* were higher between May and October (0.85) and in May (0.88). A very sharp declining trend from November to December was noticed in both sexes of this species (Fig. 4b). Months where higher K values were recorded for both species as stated above, indicate that fish were in a better condition during these months compared to any other period in the present study (Fig. 4a & b). The condition factor (K) revealed significant differences between sexes in both species; *S. commersonnii* (*t* test, t = 2.99; $P < 0.05$) and *A. sirm* (*t* test, t = -9.09; $P < 0.001$).

## Size at first maturity

Males of both species attained first sexual maturity ($L_{M50}$) at a small size compared to female individuals. The size at first sexual maturity for male and female of *S. commersonnii* were estimated to be 57.7 mm and 66.2 mm respectively (Fig 5a). For *A. sirm,* the sizes were 147.7 mm for males 169.2 mm for females (Fig. 5b).

The monthly sex ratio in *S. commersonnii* indicated that males dominated the catch for more than six

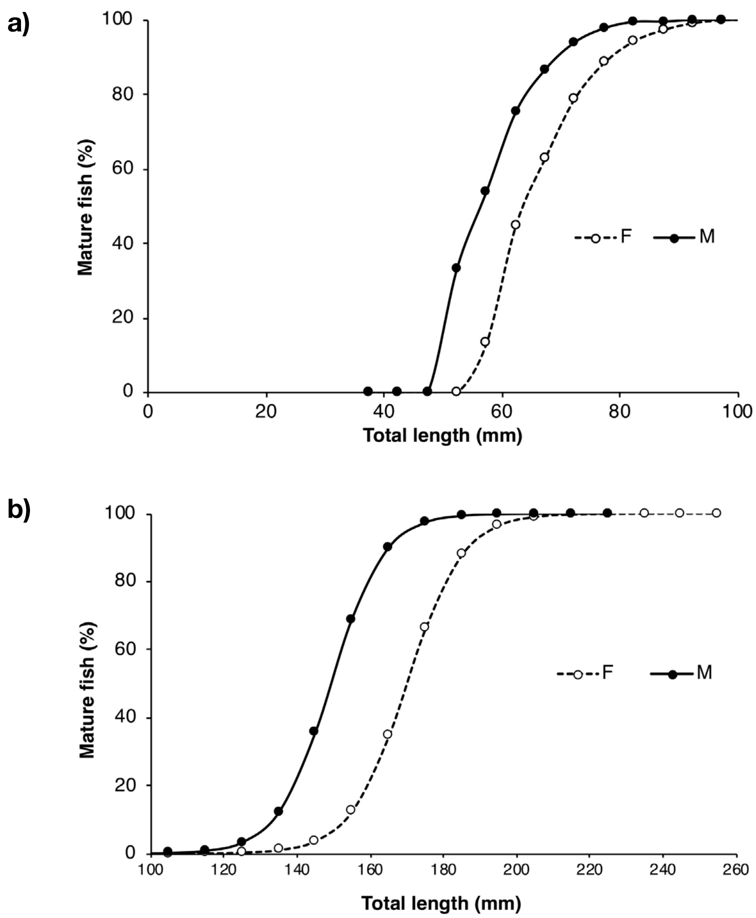


**Figure 5.** Size at first sexual maturity of (a) *S. commersonnii*, and (b) *A. sirm* from both Sahare and Vyeru sites.

months with a peak in August. The highest percentage of females was in September. Undetermined (UD) specimens were found almost throughout the study period, although in small numbers compared to males and females of this species. The highest proportion of UD specimens was recorded in September. The overall sex ratio of *S. commersonnii* was 1:0.9, being significantly in favour of females ($\chi2$ = 5.9; *df* = 1; $p$ < 0.05) (Table 1). In *A. sirm*, the predominance of males was observed from August to December and February, peaking in August. Females of *A. sirm* were more abundant in January, March, May and July with the highest percentage in May. UD specimens of this species were not recorded in most of the months except in January, February and March, with the highest proportion in February (Table 2). The overall sex ratio of *A. sirm* was 1:0.98 and a Chi-square test showed no significant difference from a normal ratio of 1:1 ($\chi2$ = 0.06; *df* = 1; $p$>0.05) .

The length frequency distribution are shown in Fig. 6 a and b. The total length of *S. commersonnii* and *A. sirm* in the fishery varied from 47 mm to 102 mm and from 65 mm to 255 mm, respectively. Variations in sex ratio with size revealed that females of *S. commersonnii* predominated in larger size classes between 91 and 105 mm TL ($\chi2$ = 4.4 *df* = 1; $p$ < 0.05) while males dominated in smaller size classes between 61 and 90 mm TL ($\chi2$ = 7.7; *df* =1; $p$ < 0.01). A similar trend was observed in *A. sirm*, where the dominance of females was in size classes between 181 and 260 mm TL ($\chi2$ = 66.3; *df* =1; $p$ < 0.001), while males were more abundant in size classes between 150 and 180 mm TL ($\chi2$ = 63.8 *df* = 1; $p$ < 0.001).

The total fecundity ranged from 850 ova in a specimen of *S. comersonnii* of 68 mm and 1.9 g to 10,055 ova in a large *S. comersonnii* of 98 mm and 6.9 g, whereas in *A.sirm* it ranged from15,700 ova in a small fish of 170 mm and 35.7 g to 96,500 ova in a large fish of 258 mm and 94.5 g. The mean (±SE) fecundity of *S. comersonnii* and *A. sirm* was 5, 134. 66 ± 136.94 ova and 47,029.03 ± 1,435.13 ova, respectively. The relative fecundity of *S. comersonnii* ranged from 459.5 to 1448.8 ova per gram

**Table 1.** Monthly variation in sex ratio of *S. commersonnii* collected from Sahare and Vyeru landing sites from August 2016 to July 2017.

| Months | Total no. of specimens | UD | Male No. | % | Female No. | % | Sex ratio (M:F) | Chi-square values |
|---|---|---|---|---|---|---|---|---|
| Aug. 16 | 331 | 1 | 187 | 56.7 | 143 | 43.3 | 1:0.76 | 5.87* |
| Sept | 252 | 24 | 98 | 43.0 | 130 | 57.0 | 1:1.33 | 4.49* |
| Oct | 271 | 0 | 151 | 55.7 | 120 | 44.3 | 1:0.79 | 3.55 |
| Nov | 311 | 11 | 154 | 51.3 | 146 | 48.7 | 1:0.95 | 0.21 |
| Dec | 513 | 4 | 280 | 55.0 | 229 | 45.0 | 1:0.82 | 5.11* |
| Jan. 17 | 280 | 1 | 138 | 49.5 | 141 | 50.5 | 1:1.02 | 0.03 |
| Feb | 331 | 3 | 155 | 47.3 | 173 | 52.7 | 1:1.12 | 0.99 |
| Mar | 344 | 11 | 188 | 56.5 | 145 | 43.5 | 1:0.77 | 5.55* |
| Apr | 165 | 8 | 77 | 49.0 | 80 | 51.0 | 1:1.04 | 0.06 |
| May | 302 | 9 | 159 | 54.3 | 134 | 45.7 | 1:0.84 | 2.13 |
| Jun | 265 | 13 | 131 | 52.0 | 121 | 48.0 | 1:0.92 | 0.39 |
| Jul | 266 | 10 | 122 | 47.7 | 134 | 52.3 | 1:1.10 | 0.56 |
| Pooled | 3631 | 95 | 1840 | 52.0 | 1696 | 48.0 | **1:0.92** | 5.86* |

*Significant at 0.05 level of error or 95% confidence

**Table 2.** Monthly variation in sex ratio of *A. sirm* collected from Sahare and Vyeru landing sites from August 2016 to July 2017.

| Months | Total No. of specimens | UD | Male No. | % | Female No | % | Sex ratio (M:F) | Chi-square values |
|---|---|---|---|---|---|---|---|---|
| Aug. 16 | 85 | 0 | 58 | 68.2 | 27 | 31.8 | 1: 0.47 | 11.31** |
| Sept | 300 | 0 | 144 | 48.0 | 156 | 52.0 | 1 :1.08 | 0.48 |
| Oct | 50 | 0 | 26 | 52.0 | 24 | 48.0 | 1 : 0.92 | 0.08 |
| Nov | 136 | 0 | 74 | 54.4 | 62 | 45.6 | 1 :0.84 | 1.06 |
| Dec | 124 | 8 | 59 | 50.9 | 57 | 49.1 | 1 : 0.97 | 0.03 |
| Jan. 17 | 34 | 0 | 15 | 44.1 | 19 | 55.9 | 1: 1.27 | 0.47 |
| Feb | 99 | 63 | 23 | 63.9 | 13 | 36.1 | 1 :0.57 | 2.78 |
| Mar | 89 | 24 | 24 | 36.9 | 41 | 63.1 | 1 :1.71 | 4.45 * |
| Apr | | | | | | | | |
| May | 27 | 0 | 8 | 29.6 | 19 | 70.4 | 1: 2.38 | 4.48 * |
| Jun | 154 | 0 | 77 | 50.0 | 77 | 50.0 | 1 :1.0 | - |
| Jul | 61 | 0 | 28 | 45.9 | 33 | 54.1 | 1:1.18 | 0.41 |
| Pooled | **1159** | **95** | **536** | **50.4** | **528** | 49.6 | 1: 0.98 | 0.06 |

*Significant and ** very significant at 0.05 level of error or 95% confidence

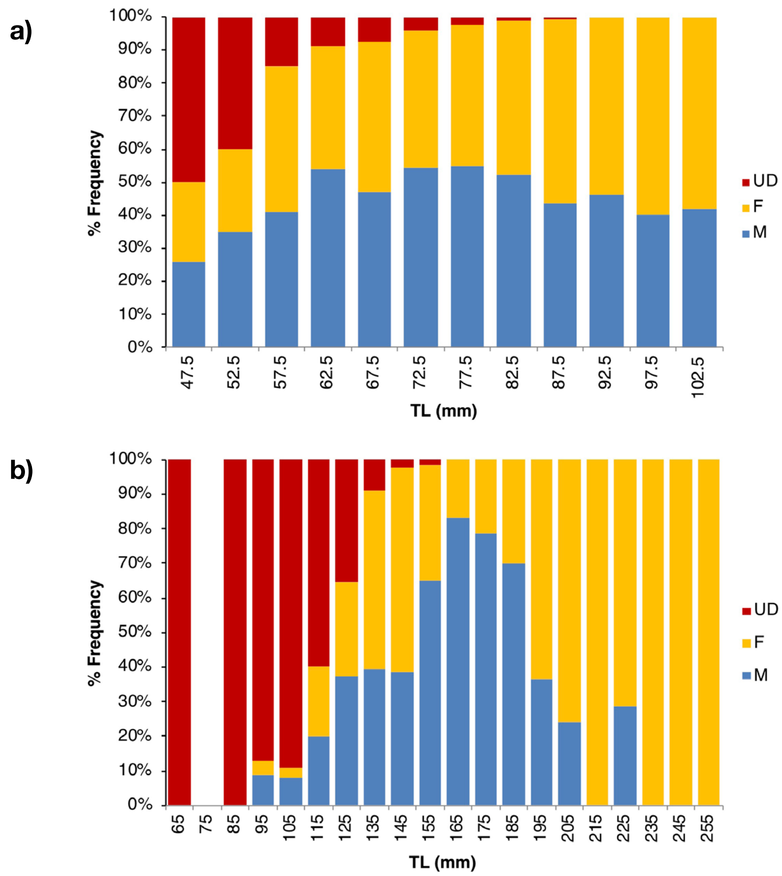


**Figure 6.** Length-frequency distribution of male, female and undetermined (a) *S. commersonnii*, and (b) *A. sirm*.

of fish with a mean (±SE) of 1047.01 ± 14.2 ova per gram of fish; whereas in *A.sirm* it ranged from 374.4 to 1075.8 ova per gram of fish and averaged (±SE) at 723.5 ± 14.6 ova per gram of fish.

The power function revealed a significant correlation between total length (TL) of fish and total fecundity (Y), with allometric growth in both species ($Y= 0.000003TL^{4.77}$, r = 0.76, *df* = 144, P< 0.001 in *S. comersonnii* (Fig. 7a); and $Y = 0.0000007\,TL^{4.72}$, r = 0.68, *df* = 123, P< 0.001 (Fig. 7b) in *A. sirm*). The correlation between fish weight and total fecundity in both species showed a positive linear relationship; Y= - 4004.7 + 1916.8 TW, and a strong correlation coefficient (r = 0.9, *F*= 6.82, *df* = 144, P < 0.001) in *S. comersonnii*, and Y= - 17757.5 + 1014.6, r = 0.9, *F*= 6.82, *df* = 144, P < 0.001 in *A. sirm*.

## Discussion

The findings of this study revealed that the two species exhibit protracted spawning. Moreover, mature individuals of both male and female *S. commersonnii* with ripe gonads were collected throughout the sampling period, which suggests that the species spawns throughout the year on the Tanzanian coast. This pattern agrees with other studies on *Stolephorus* species; for instance Basilone *et al.* (2006) and Rohit and Gupta (2008) reported similar spawning behaviour in stolephorid anchovies and *Stolephorus waitei*. On the other hand, extended spawning in *A. sirm* has also been reported elsewhere in the world; for instance Conand (1991), Veerappan *et al.* (1997), and Authukoorala *et al.* (2015).

A prolonged spawning period for several months or during the entire year is a character of an indeterminate serial spawning fish (George, 1998). Serial spawners (including anchovies and most clupeids) are known to produce more eggs compared to total spawners (eg. eels - *Anguilla spp*). Most serial spawners, especially anchovies, are small in body size and normally do not have sufficient space in their body cavities to accommodate the total amount of eggs produced per year at the same time; therefore they need to spawn in batches for long periods (Maack and George, 1999). Palomera (1992) related random spawning over time in clupeids to a strategy that enables at least some batches of larvae to encounter favourable environmental conditions to enhance individual survival. The scattered spawning peaks (Fig. 2a & 3a) observed

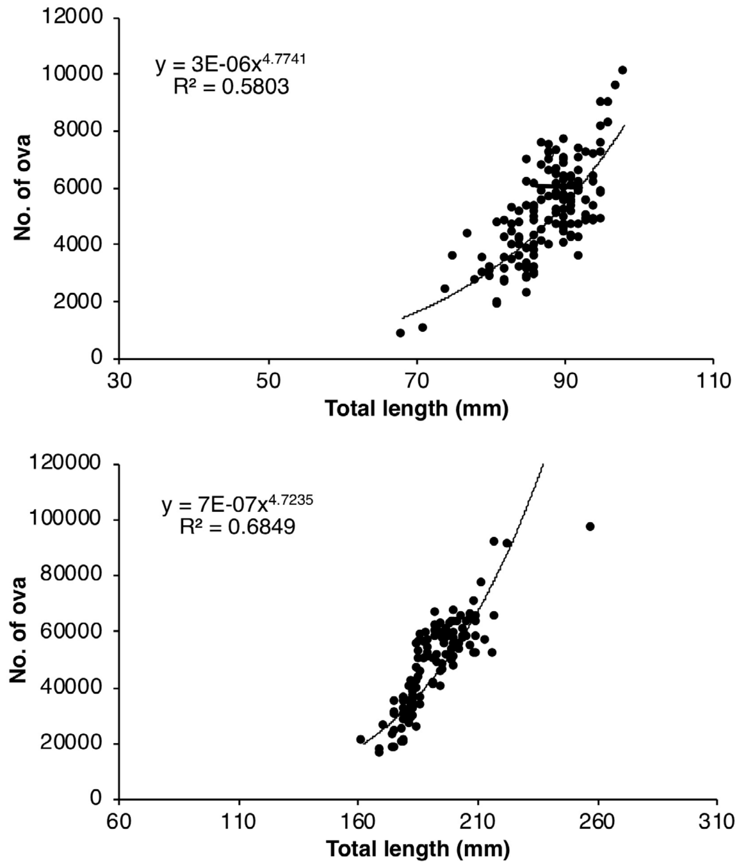


**Figure 7.** Length-fecundity relationship of a) *S. commersonnii* (N= 145), and b) *A. sirm (N* = 124).

in the present study support the point that *S. commersonnii* and *A. sirm* are serial spawners.

The peak spawning period of *S. commersonnii* during this study falls virtually at the same time as that of *Stolephorus devisi* as reported by Rohit and Gupta (2008). This similarity could probably be attributed to the fact that the two species share many morphological and ecological similarities, hence their life histories do not differ much. However, the peak spawning seasons of *S. commersonnii* reported during this study are partially comparable to that of Luther *et al.* (1992) who found that this species exhibited two spawning peaks; February - October and March – May. Such variations suggest flexibility in *S. commersonnii* to regulate their reproductive period according to environmental factors, of which nutrient availability, photoperiod and temperature have been reported as the main factors affecting reproduction of engraulids in coastal waters (Silva *et al.*, 2003; Araújo *et al.*, 2008). Several studies have also reported different spawning seasons in anchovies (engraulidae) in tropical and sub-tropical waters, including Kim *et al.* (2013) and Andamari *et al.* (2002).

The condition factor (K) is another aspect widely used in studies on reproductive biology of different fish species, predicting that individuals with higher K values are in better physiological condition (Rodrigues-Filho *et al.,* 2011). The present study showed that K values for both sexes of *S. commersonnii* were higher in one of the peak spawning periods (October) (Fig. 4a) and then exhibited a declining trend in the other two peak periods (January and August). A similar trend was observed in *A. sirm* where the highest K value (0.89) seemed to correspond with the peak spawning period (September) in females, and a slightly lower value (0.82) in the peak spawning period (August) for males, as compared to the values recorded in May and October (Fig. 4b). The slight decline in K values observed during peak spawning of these two species indicates high energy expenditure during spawning (Rodrigues-Filho *et al.,* 2011) which probably resulted in poor fish health condition as K values lower than 1 implies the fish is in poor health (Bhattacharya and Sree, 2012). This could result in minor effects on newly fertilized eggs, rates of hatching and larval survival of these species (Souza-Conceição *et al.*, 2005).

The size at first maturity of male and female *S. commersonnii* in the present study are comparable to that reported by Alba *et al.* (2016) for unsexed individuals at 71 mm, but lower than those (110 mm and 109 mm) reported by Luther (1979) and Andamari *et al.* (2002), respectively. In addition, the sizes that were obtained for both sexes of *A. sirm* during this study almost concur with those reported by Veerappan *et al.* (1997) at 150 mm and 160 mm for males and females, respectively. However, Conand (1991) found sizes at first maturity for *A. sirm* to be higher (between 175-179 mm in males and 180-184 mm in females) as compared to the ones observed in the present study. This signifies that fishes that belong to the same species may attain first maturity at different sizes depending on the condition of the environments they inhabit and other associated factors. This is in agreement with other scientists who suggested that the growth of fish could be retarded by environmental conditions and food resources (Wootton, 1990) and pressure exerted from fishing activities (Baali *et al.*, 2017).

Moreover, changes in size at first maturity may be ascribed to the different strategies utilised by fish in different environments to better adapt to environmental conditions (Baali *et al.*, 2017). This study also demonstrated that males of both species attained first sexual maturity at smaller sizes than females. This could either be due to variations in the quantity of energy reserves available for gonad development, as a direct effect (Morgan, 2004), or due to changes in growth, which influence the onset of gonadal maturation, as an indirect effect (George and Mikko, 2004). The males of *S. commersonnii* and *A. sirm* matured earlier than the females, probably because they required less energy reserves for gonadal maturation.

The overall sex ratio observed in *S. commersonnii* during this study concurs with the observation by Rohit and Gupta (2008), who reported a sex ratio of 1:07 in *Stolephorus insularis* along the Manglore-Malpe coast of India. Furthermore, the current study showed an insignificant difference from the expected population ratio of 1:1 in *A. sirm*. A similar trend was found in other clupeid species like *Sardinella lemuru* in Western Australia (Gaughan and Mitchell, 2000), and *Sardinops sagax* (Gaughan *et al.*, 2008), but differed from that reported by Jayasuriya (1989) and Veerappan *et al.* (1997) who found a predominance of females in the overall sex ratio of *A. sirm* in Sri lanka and India.

*S. commersonii* and A. *sirm* revealed a skewed size-dependent sex ratio with females dominating in larger size classes during this study. This was also evident in other tropical and sub-tropical waters for *Stolephorus hetrolobus* (Milton *et al.*, 1990), and anchovies like *Engraulis encrasicolus* (Baali *et al.*, 2017) and *A. sirm* (Veerappan *et al.*, 1997). This could be ascribed to a number of factors including faster growth of females resulting in them becoming vulnerable to fishing gear, and displaying different migratory movements as compared to males (Abderrazik *et al.*, 2016), and natural mortality differing between the sexes (Turner *et al.*, 1983). The most likely hypothesis in the case of the present study could be migration. Anchovies and clupeids of the same cohort are known to move in large schools over long distances (hundreds of kilometres) searching for food and spawning. These types of movements are very common in these fishes as a mechanism to increase survivorship by diminishing detection by predators (Swartzman, 1991), and confusing predators by complex coordinated manoeuvres (Eshel, 1978) while looking for food and undertaking other activities. It is probable that this kind of spatial movement affected all size classes of both sexes and species during this study.

The monthly deviation in sex ratio observed in both species during this study could be explained by migration or behavioural differences between the sexes which allow one sex to be more easily caught than the other. A similar variation in sex ratio in other anchovies has been found off California (Klingbeil, 1978) and in Peru (Alheit *et al.*, 1984). This deviation has also been reported in other cluipeids such as *Sardinella longiceps* along the coast of Ratnagiri off Maharashtra in India (Deshmukh, *et al.*, 2010). It has been indicated that such variations in the sex ratio are difficult to describe, but some authors have this to a combination of factors including availability of the food in the region, as found by Nikolsky (1969) who reported that when food is abundant in a particular area, females predominate, and the situation changes where food is limited. The spatial segregation of spawning and non-spawning fish is another factor that has been observed to cause variation in some anchovy and clupeid species (Williams and Clarke, 1983). Females of these families tend to separate either by depth or area from the non-spawners, migrating with predominantly males to establish spawning schools (Alheit *et al.*, 1984). The observed monthly variation in sex ratio of the two species investigated in the present study could be attributed to one or a combination of all these factors.

The present study found a direct proportional relationship between size (total length and weight) and fecundity of mature and gravid females in both species. These findings comply with Rao (1988) in *Stolephorus spp* and Veerappan *et al*. (1997) in *A. sirm*. Other species in the family Clupeidae have also shown this kind of relationship; for instance Zaki *et al*. (2012) reported the fecundity of *Sardinella longiceps* to increase with increase in size (ranging from 22,456 ova at 159 mm TL and 36 g, to 61, 867 ova at 187 mm TL and 54 g). This relationship was found in both *S.commersonni* and *A. sirm* during this study, and could be explained by the fact that as the fish increases in size (length and weight) more space is created for accommodating eggs. This makes sense in that an increment in body size tends to increase the size of the body cavity, and ensures availability of more energy for the production of many eggs (Jonsson and Jonsson, 1997; Singh *et al*., 1982). Moreover, this study found the fecundity of *S. commersonnii* and *A. sirm* to range between 850 at 68 mm TL – 10055 eggs at 98 mm TL, and 17500 at 170 mm TL – 96,500 eggs at 258 mm TL respectively; being higher than the ranges of *S. devis* (162 eggs to 3166 at a size between 61-96 mm TL) and slight lower than that of *A. sirm* (21,800 eggs at 121 mm TL to 124, 800 at a size of 226 mm TL) as reported by Rao (1988) and Veerappan *et al* (1997). Such variation in fecundity could be attributed to differences in environmental conditions that may influence food availability in the area, but also to high fishing pressure which can stress the fish and affect reproduction processes.

## Conclusion

This study has confirmed that both species are multiple spawners. Moreover, intensive spawning of both sexes of *S. commersonnii* occurred in August, October and January while in *A. sirm* this occurred during August and September for males and females respectively. Taking this into consideration, it is recommended that the responsible authorities start practicing management measures such as seasonal closures during peak seasons to reduce growth overfishing of these species. However, most emphasis should be put on *S. commersonnii*, which is the most abundant small pelagic species from Tanga coastal waters. This species faces continual heavy exploitation pressure due to high demand in and outside the country.

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## References

Abderrazik W, Baali A, Schahrakane Y, Tazi O (2016) Study of reproduction of sardine, *Sardina pilchardus* in the North of Atlantic Moroccan area. AACL Bioflux 9: 507-517

Alba BE, Chiuco BM, Rubia CM (2016) Mesh size selectivity of boat seine and stationary lift net for catching anchovy and white sardine in Sorsogon Bay, Philippines. International Journal of Fisheries and Aquatic Studies 4: 265-273

Alheit J (1989) Comparative spawning biology of anchovies, sardines and sprats. Rapports et Process-verbaux des Reunions, Conseil International pour I'Exploration de la Mer 191:7-14

Alheit J, Alarcon VH, Macewicz BJ (1984) Spawning frequency and sex ratio in Peruvian anchovy. California Cooperative Oceanic Fisheries Investigations Report 25: 43-52

Andamari R, Milton D, Zubaidi T (2002) Reproductive biology of five species of anchovy (Engraulidae) from Bima Bay, Sumbawa, Nusa Tenggara. Indonesia. Journal of Agriculture Science 3: 37-42

Araújo FG, Silva MA, Santos JNS, Vasconcellos RM (2008) Habitat selection by anchovies (Clupeiformes:Engraulidae) in a tropical bay at Southeastern Brazil. Neotropical Ichthyology 6: 583-590

Athukoorala AASH, Bandaranayaka KHK, Haputhantri SSK (2015) A study on some aspects of reproductive biology and population characteristics of *Amblyigaster sirm* in the west coast of Sri Lanka. International Journal of Fisheries and Aquatic Studies 2: 41-45

Azza AE (1992) Biological studies on Lizard fishes *Saurida undosquamis* (Pisces, Synodontidae) from the Gulf of Suez. MSc Thesis. Faculty of Science, Ain Shams University. 330 pp

Baali A, Bourassi H, Falah S, Abderrazik W, El Qoraychy I, Amenzoui K, Yahyaoui A (2017) Study of reproduction of anchovy *Engraulis encrasicolus* (Actinopterygii, Engraulidae) in the central area of the Moroccan Atlantic coast. Journal of Materials and Environmental Sciences 8: 4467-4474

Basilone G, Guisande C, Patti B, Mazzola S, Cuttitta A, Bonanno A, Vergara AR, Maneiro I (2006) Effect of habitat conditions on reproduction of the European anchovy (*Engraulis encrasicolus*) in the Strait of Sicily. Fisheries Oceanography 15: 271-280

Bhattacharya P, and Banik S (2012) Length-weight relationship and condition factor of the pabo catfish *Ompok pabo* (Hamilton, 1822) from Tripura, India. Indian Journal of Fisheries 59: 141-146

Chullasorn S, Martosubroto P (1986) Distribution and important biological features of coastal fish resources in Southeast Asia. FAO Fisheries Technical Paper 278. 73 pp

Clarke TA (1987) Fecundity and spawning frequency of the Hawaiian anchovy or Nehu, *Encrasicholina purpurea*. Fishery Bulletin of United states 85:127-138

Conand F (1991) Biology and phenology of *Amblygaster sirm* (Clupeidae) in New Caledonia, A sardine of the coral environment. Bulletin of Marine Science 48: 137-149

Deshmukh AV, Kovale RS, Sawant SM, Shirdhankar MM, Funde AB, (2010) Reproductive biology of *Sardinella longiceps* along Ratnagiri coast off Maharashtra. Indian Journal of Marine Science 39: 274-279

Duponchelle F, Panfili J (1998) Variations in age and size at maturity of female Nile tilapia, *Oreochromis niloticus*, populations from man-made lakes of Côte dIvoire. Environmental Biology of Fishes 52: 453-465

Eshel I (1978) On a prey–predator nonzero-sum game and the evolution of gregarious behaviour of evasive prey. The American Naturalist 112: 787– 795

Fischer W, Bianchi G (eds) (1984) FAO species identification sheets for fishery purposes. Western Indian Ocean (Fishing Area 51). Danish International Development Agency (DANIDA)/Food and Agricultural Organisation of the United Nations (FAO), Vol. 1-6, Rome

Franco ACS, Daniel SB, David MWZ, Luciano ND (2014) Reproductive biology of *Cetengraulis edentulus* (Cuvier, 1829), the major fishery resource in Guanabara Bay, Brazil. Neotropical Ichthyology 12: 819-826

Gao D, Wan R, Ma Q, Zhang X, Bian X (2016) Development of eggs and larvae of *Stolephorus commersonnii* and taxonomic key to fish eggs of the Clupeidae and Engraulidae off China. Marine Biology Research 12: 255-267

Gaughan D, Mitchell RWD, (2000) the biology and stock assessment of the tropical sardine, *Sardinella lemuru*, off the mid-west coast of Western Australia. Final report to fisheries research and Development Corporation on project No. 95/037. Fisheries Research Report No. 119, Department of Fisheries, Western Australia. 136 pp

Gaughan D, Craine M, Stephenson P, Leary T, Lewis P (2008) Regrowth of pilchard (*Sardinops sagax*) stocks off southern WA following the mass mortality event of 1998/99. Final report to fisheries research and Development Corporation on project No. 2000/135. Fisheries Research Report No. 176, Department of Fisheries, Western Australia. 82 pp

George MR, (1998) Die Fortpflanzungsbiologie zweier pelagischer Fischarten *Sardinops sagax* (Jenyns, 1842) (Clupeidae) und *Trachurus picturatus murphyi* Nichols 1920 (Carangidae) im Auftriebsgebiet Nordchiles. Biblothek Natur & Wissenschaft Bd. 14, Verlag Natur & Wissenschaft, Solingen. 133 pp

George HE, Mikko H (2004) Maturity changes in Norwegian spring-spawning herring before, during, and after a major population collapse. Fisheries Research 66: 299-31

Holden MJ. Raitt DFS, (1974) Manual of fisheries science. FAO Fisheries Technical Paper. 115 pp

Jayasuriya PMA (1989) Some aspects of the biology and population of *Amblygaster sirm* (Walbaum) from the West coast of Sri linka. Journal of the National Science Foundation of Sri Lanka 17:53-66

Jonsson N, Jonsson B (1997) Energy allocation in polymorphic brown trout. Functional Ecology 11: 310-317

Kamukuru AT (2009) Trap fishery and reproductive biology of the Whitespotted Rabbitfish *Siganus sutor* (Siganidae), within the Dar es Salaam marine reserves, Tanzania. Western Indian Ocean Journal of Marine Science 8:75-86

Kamukuru AT, Mgaya YD (2004) Effects of exploitation on reproductive capacity of blackspot snapper, *Lutjanus fulviflamma* (Pisces: Lutjanidae) in Mafia Island, Tanzania. African Journal of Ecology 42: 270-280

Kim JY, Lee KS, Kim SS, Choi SM (2013) Environmental factors affecting anchovy reproductive potential in the southern coastal waters of Korea. Animal Cells and Systems 17: 133-140

King JR, McFarlane GA (2003) Marine fish life history strategies: Applications to fishery management. Fisheries Management and Ecology 10: 249-264

Klingbeil RA (1978) Sex ratio of the northern anchovy, *Englauris mordax* off Southern Calfonia. Calfornia Fish & Game 64: 200-2009

Lamtane HA, Pratap HB, Ndaro SMG (2007) Reproductive biology of *Gerres oyena* (Pisces: Gerreidae) along the Bagamoyo coast, Tanzania. Western Indian Ocean Journal of Marine Science 6: 29-35

Luther G, Rao NVK, Gopakumar G, Muthiah C, Pillai GN, Rohit P, Kurup NK, Reuben S, Devadossy P, Rao SG, Bennet SP, Radhakrishnan SN (1992) Resource characteristics and stock assessment of whitebaits. Indian Journal of Fisheries 39: 152-168

Luther G (1979) Anchovy fishery of southwest coast India with notes on the characteristics of the resources. Indian Journal of Fisheries 26: 23-29

Maack G, George MR (1999) Contributions to the reproductive biology of *Encrasicholina punctifer* Fowler, 1938 (Engraulidae) from West Sumatra, Indonesia. Fisheries Research 44: 113-120

Madan M, Velayudhan AK (1984), A few observations on the taxonomy and biology of *Nemipterus delagoe* Smith from Vizhinjam. Indian Journal of Fisheries 28: 26-34

Mcgowan MF, Berry FH (1983) Clupeiformes: rdevelopment and Relationships. In: Blaxter J HS (eds) Ontogeny and Systematics of Fishes 8: 108-126

Meng QW, SuJ X, Miao XZ (1995) Clupeomorpha. In: Meng QW, Su JX, Miao XZ (eds)

Systematics of fishes. China Agriculture Press, Beijing. pp 153-72

Milton DA, Blaber SJM, Rawlinson NJF (1994) Reproductive biology and egg production of three species of Clupeidae from Kiribati, tropical Pacific. Fisheries Bulletin 92: 102-121

Morgan M J (2004) The relationship between fish condition and the probability of being mature in American plaice (*Hippoglossoides platessoides*). ICES Journal of Marine Science 61: 64-70

Murua H, Kraus G, Saborido-Rey F, Witthames PR, Thorsen A, Janquera S (2003) Procedures to estimate fecundity of marine fish species in relation to their reproductive strategy. Journal of Northwest Atlantic Fishery Science 33: 33-54

Nikolsky GV (1969) Theory of fish population dynamics. Translated by Bradley JES. Oliver and Boyd Limited, Edinburg

Nunes C, Silva A, Soares E, Ganias K. (2011) The use of hepatic and somatic indices and histological information to characterize the reproductive dynamics of Atlantic sardine *Sardina pilchardus* from the Portuguese coast. Marine and Coastal Fisheries 1-3 (1): 127-44

Palomera I (1992) Spawning of anchovy *Engraulis encrasicolus* in the Northwestern Mediterranean relative to hydrographic features in the region. Marine Ecology Progress Series 79: 215- 223

Pradeep HD, Swapnil SS, Kar AB (2014) Age, growth and mortality of *Amblygaster sirm* (Walbaum, 1792) from Andaman waters. Journal of the Andaman Science Association 19: 201-208

Rao GS (1988) Biology of *Stolephorus devisi* (Whitley) from Mangalore area Dakshina Kannada. Journal of the Marine Biological Association of India 30: 28-37

Rodrigues-Filho JL, Verani JR, Peret AC, Sabinson LM, Branco JO (2011) The influence of population structure and reproductive aspects of the genus *Stellifer* (Oken, 1817) on the abundance of species on the southern Brazilian coast. Brazilian Journal of Biology 71: 991-1002

Rohit P, Gupta CA (2008) Whitebait fishery of Mangalore - Malpe, Karnataka during 1997-2002. Indian Journal of Fisheries 55: 211-214

Silva MA, Araújo FG, Azevedo MCC, Mendonça P (2003) Distribuição espacial e temporal de *Cetengraulis edentulus* (Cuvier, 1829) (Actinopterygii, Engraulidae) na Baía de Sepetiba, Rio de Janeiro, Brasil. Revista Brasileira de Zoologia 20: 577-581

Silva GC, Castro ACL, Gubiani EA (2005) Estrutura populacional e indicadores reprodutivos de *Scomberomorus brasiliensis* no litoral ocidental maranhense. Acta Scientarium Biological Sciences 27: 383-389

Singh HR, Nauriyal BP, Dobriyal AK (1982) Fecundity of a hillstream minor carp *Puntius chilinoides* (McClelland) from Garhwal Himalaya. Journal of the Indian Academy of Sciences 91: 487-491

Souza-Conceição J M, Rodrigues-Ribeiro M, Castro- Silva M A (2005) Dinâmica populacional biologia reprodutiva e o ictioplâncton de *Cetengraulis edentulus* na enseada do Saco dos Limões, Florianópolis, Santa Catarina, Brasil. Revista Brasileira de Zoologia 22: 953-961

Swartzman G (1991) Fish school formation and maintenance: a random encounter model. Ecological Modelling 56: 63-80

Turner SC, Grimes CB, Able KW (1983) Growth, mortality, and age/size structure of the fisheries for the tilefish, *Lopholatilus chaemaelonticeps*, in the middle Atlantic-Southern New England region. Fishery Bulletin of the United States 81: 751-763

Veerappan N, Ramanathan M, Ramaiyan V (1997) Maturation and spawning biology of *Amblygaster sirm* from Parangipettai southeast coast of India. Journal of the Marine Biological Association 39: 89-96

Williams VR, Clarke TA, (1983) Reproduction, growth, and other aspects of the biology of the gold spot herring, *Herklotsichthys quadrimaculatus* (Clupeidae), a recent introduction to Hawaii. Fishery Bulletin of the United States 81: 587-597

Wootton RJ (1990) Ecology of teleost fishes. Fish and Fisheries Series 1. Chapman & Hall, London. 403 pp

Zaki S, Jayabalan N, Al-Kiyumi F, Al-Kharusi L, Al-Habsi S (2012) Maturation and spawning of the Indian oil sardine *Sardinella longiceps* Val. From the Sohar coast, Sultanate of Oman. Journal of the Marine Biological Association of India [doi: 10.6024/ jmbai.2012.54.1.01722-13]

Zhang SY (2001) Clupeiformes. In: Zhang SY (ed) Fauna Sinica Osteichthyes, Acipenseriformes, Elopiformes, Clupeiformes, Gonorynchiformes. Science Press, Beijing. pp 52-159

# Age, growth and mortality of the anchovy *Stolephorus commersonnii* (Lacepède, 1803) (Clupeiformes) caught off the coast of Tanga, Tanzania

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## Abstract
The population dynamics of *Stolephorus commersonnii* (Lacepède, 1803) from a ringnet fishery operating off the northern coast of Tanga Region were evaluated based on monthly length-frequency data collected from August 2016 to August 2017. The total length (TL) and total weight (TW) of 14,410 individuals ranged from 22 to 130 mm and from 0.39 to 14.64 g respectively. *S. commersonnii* exhibited a negative allometric growth pattern with the length-weight relationship model: $W = 0.00001 \times L^{2.886}$. The von Bertalanffy growth function was $L_t = 86.03 \times (1 - e^{-1.19(t - (-0.01))})$ using ELEFAN I from the FiSAT II software tool package. Growth performance index and longevity were estimated at ($\phi$) = 3.9 and $T_{max}$ = 2.5 yrs, respectively. The total (Z), fishing (F) and natural (M) mortalities were determined at 1.39, 0.53 and 0.86 $yr^{-1}$, respectively. The current exploitation rate ($E_{cur}$) was estimated at 0.38. *S. commersonnii* exhibited a year-round breeding pattern, with two recruitment peaks in March and June/July. Length-at-first-capture ($L_{c50}$) and length-at-first-sexual maturity ($L_{m50}$) were 40.51 and 57.35 mm TL, respectively, suggesting growth overfishing. The stock of anchovy indicates an overfishing scenario requiring management intervention such as reducing fishing effort levels, increasing mesh sizes and introducing seasonal closures during peak spawning periods.

**Keywords:** Nitrate, Silicate, Productivity, Kenya, North Kenya Bank

## Introduction
Anchovies belong to the order Clupeiformes within the suborder Clupeoidei comprising four families (Whitehead *et al*., 1988). Two of these families, the anchovies (Engraulidae) and sardines or herrings (Clupeidae) form the bulk of small fish species in the pelagic ecosystem and fisheries of the world oceans (FAO, 2016; Checkley *et al*., 2017). Anchovies have been reported to exhibit several biological characteristics 9such as short plankton-based food chains, fast growth, short-lived, relatively low fecundities and year-round spawning of some species) making them highly sensitive to environmental variability (Kawasaki, 1980; Checkley *et al*., 2009). For example, clupeoid populations are noted for exhibiting large spatial and temporal fluctuations in abundance under the influence of environmental conditions (Cole and McGlade, 1998).

Several studies in the marine ecosystem have focused on areas subjected to upwelling events where anchovies and sardines cohabit (e.g. Benguela Current and Peru Current ecosystems) and fluctuations in abundance of the populations of both species have been reported (Lluch-Belda *et al*., 1989; Barange *et al*., 2009). Furthermore, Lluch-Belda *et al.* (1989) and Lindegren *et al.* (2013) found that the behavior of forming large aggregations subject clupeoid populations to high fishing

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pressure causing concern about the management of these unpredictable fisheries. However, these small pelagic fish species are reported to be resilient and can withstand high levels of predation and fishing pressure due to their high turnover rates (Mannini, 1992).

Ecologically, the anchovies play a paramount role in repackaging energy consumed by higher trophic levels (Checkley *et al*., 2017; Guénette *et al*., 2014). Arneril *et al*. (2011) observed that anchovies serve as zooplankton predators as well as prey for many other marine organisms including medium to large pelagic fishes and cetaceans. Economically, anchovies tend to be an easy target for both artisanal and commercial fishers due to their aggregative distribution patterns and formation of dense schools (Pitcher, 1995).

The pelagic fisheries resources off the coast of Tanzania are largely multispecies and multisector, with the small pelagic species, locally referred to as "*dagaa*", forming an important component of the sector (Bodiguel and Breuil, 2015). The official statistics of marine fish production in the Tanzania's territorial and internal waters is close to 70,000 tons per year with small pelagic fishes accounting for approximately one third of total catch (Bodiguel and Breuil, 2015). The anchovies are commercially important and form a significant component of the marine fisheries catch, serving as a fish protein source for most households in Tanga Region. The species are often harvested by small scale fishers who deploy small mesh-sized ringnets and purse seine nets using lights at night. Other gear for catching small pelagic fish species include small mesh-size gillnets and beach seines, which are considered illegal. The recently developed processing method for anchovies (salt-boiled and sun dried) was in response to the demands for fish products in the inland regions of Tanzania and the Democratic Republic of Congo (Fujimoto, 2018). Furthermore, Bodiguel and Breuil (2015) indicated that anchovies are marketed fresh in small quantities in the hinterland markets near the coast.

Despite the significant economic and ecological importance of *S. commersonnii* in the coastal waters of Tanga Region, there is a paucity of information on population parameters and stock status. Knowledge of population dynamics is essential for the development of fish stock assessment programmes with the aim of providing advice on the optimum exploitation level for sustainability of the species. In view of this limitation, the primary objective of this study was to establish the population dynamic parameters of Commerson's anchovy to evaluate its current exploitation rate within the northern coastal waters of Tanga Region.

## Materials and Methods

### Study area

The study focused on the northern coast of Tanga Region which comprises two coastal districts, namely Mkinga and Tanga City. Fish sampling was conducted at the two fish landing sites of Vyeru and Sahare corresponding to Mkinga and Tanga City respectively (Fig. 1). The criteria for the selection of study sites were based on geographical location, as well as the level and type of fishing activity (specifically using ringnets to target small pelagic fish species).

### Fish sampling

*S. commersonnii* individuals were randomly sampled on a monthly basis for ten consecutive days from local fishers operating ringnets using motorized wooden boats between August 2016 and August 2017. The ringnets had a mesh size of 8 – 10 mm, were 80 m in length and had a depth of about 12 m. Total length (TL) was determined using a fish measuring board to the nearest mm and total weight (TW) to the nearest 0.01 g using an electronic scale. Samples were unsexed. Both researchers and local enumerators participated in fish sampling and measurements. The species was identified using the fish identification keys of Fischer and Bianchi (1984) and Smith and Heemsta (2003).

### Data analysis

The relationship between body length (L) and weight (W) was determined using the length-weight relationship (LWR) model: $W = aL^b$ where '$a$' and '$b$' are constants for the model (Le Cren, 1951). The Student's $t$-test was used to test for significant differences of regression coefficients between the calculated '$b$' and cube law of the LWR model. The relative condition factor ($K_n$) was calculated according to Le Cren (1951): $Kn = \frac{W}{aL^b}$.

The monthly length frequency data were grouped into 5 mm size class intervals for the estimation of growth parameters. The asymptotic length ($L_\infty$) and instantaneous growth rate (K) were determined using the ELEFAN I from the FiSAT II software tool package (FAO-ICLARM Stock Assessment Tools, Ver 1.2.2, 2005) to generate the von Bertalanffy growth function (VBGF): $L_t = L_\infty \times (1 - e^{-K(t - (-t0))})$. The theoretical age at birth ($t_0$) was calculated independently, using the empirical formula by Pauly (1979): $Log_{10}(-t_0) = -0.3922 - 0.275 x Log_{10}(L_\infty) - 1.038 x Log_{10}(K)$. The growth performance index (ϕ) was determined following an expression by Munro and Pauly (1983): $2 \text{ x } Log_{10}(L_\infty) + Log_{10}(K)$. Longevity ($T_{max}$) was estimated according to Pauly (1983): $T_{max} = \frac{3}{K} + t_0$.

The total mortality (Z) was estimated using the FiSAT II software tool package from the length-converted catch curve of size classes descending towards the right arm. Natural mortality (M) was calculated using an empirical formula assuming the mean habitat temperature (T) to be 27° C (Pauly, 1980): $Log_e(M) = -0.0152 - 0.279 \text{ x } Log_e(L_\infty) + 0.654 \text{ x } Log_e(K) + 0.4634 \text{ x } Log_e(T)$. Fishing mortality (F) was obtained by substitution in the equation according to Gulland (1983): $F = Z - M$. The optimum fishing mortality ($F_{opt}$) was estimated using the equation by Pauly (1984): $F_{opt} = 0.4 \text{ x } M$.

The current exploitation rate ($E_{cur}$) was estimated using the expression by Gulland (1983): $E = \frac{F}{Z}$. The ascending left arm of the length-converted catch curve was used to analyze the probability of capture of each length class fitted in the FiSAT II software tool package to obtain length-at-first capture ($L_{c50}$). Additionally, the cumulative probability of capture was assessed at ($L_{c25}$) and ($L_{c75}$) corresponding to 25% and 75% respectively for the fish retained by the gear. The one-year recruitment pattern was determined using the FiSAT II software package by backward projection of the set of length–frequency data with inputs of $L_\infty$ and K. The length-at-first sexual maturity ($L_{m50}$) was estimated using the expression by Hoggarth *et al.* (2006): $L_{m50} = \frac{2 \times L_\infty}{3}$. Relative yield per recruit (Y'/R) and relative biomass per recruit (B'/R) were predicted based on the Beverton and Holt yield per recruit analysis assuming a knife-edge selection model incorporated into the FiSAT II

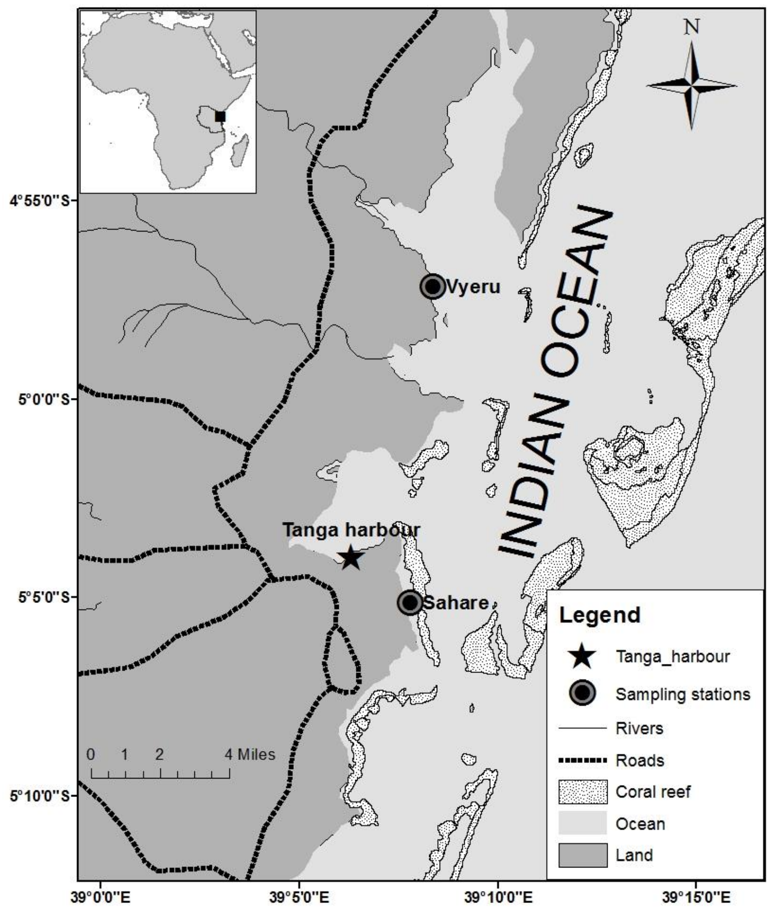


**Figure 1.** Map of the northern coast of Tanga Region showing the fish landing sites of Vyeru and Sahare.

software tool package. The outputs generated include optimum exploitation rate ($E_{max}$) to produce maximum yield per recruit, exploitation rate ($E_{0.1}$) at which the marginal increase of Y'/R is 10% of the virgin stock, and exploitation rate ($E_{0.5}$) under which the stock is reduced to half its virgin biomass per recruit. Furthermore, the yield isopleths to produce yield contours were plotted to identify the impact on yield, based on the critical values of $L_{c50}/L_{\infty}$, $E_{max}$ and M/K to help position the stock of Commerson's anchovy according to the Pauly and Soriano (1986) quadrant rule.

## Results

A total number of 14,410 individuals were measured to study the population dynamics of *S. commersonnii*. The size frequency distribution ranged from 22 to 130 mm TL weighing between 0.39 and 14.69 g TW. The mean (± s.e.) size of the exploited individuals was 77.8 ± 0. 07 mm TL with the bulk (75%) of fish occurring between 73 and 88 mm TL (Fig. 2a). The length–weight relationship parameters essential for predicting growth patterns and well-being of individuals in a population are presented in (Fig. 2b). Commerson's anchovy exhibited a negative allometric growth pattern with a mean (± s.e.) growth coefficient of $b$ = 2.89 ± 0. 01, differing significantly from the cube law of LWR ($df$ = 14308; $t$ = -16.07; $p$< 0.001). Monthly variations of growth coefficients '$b$' are shown in Table 1 indicating that both positive and negative allometric growth patterns occurred in *S. commersonnii* throughout the study period, except in December that showed an isometric growth pattern. *S. commersonnii* had a mean (± s.d.) relative condition factor of $K_n$ = 1.17 ± 0. 09, with the lowest ($K_n$ = 1.12 ± 0. 09) and highest ($K_n$ = 1.26 ± 0. 21) occurring in April/May and September respectively.

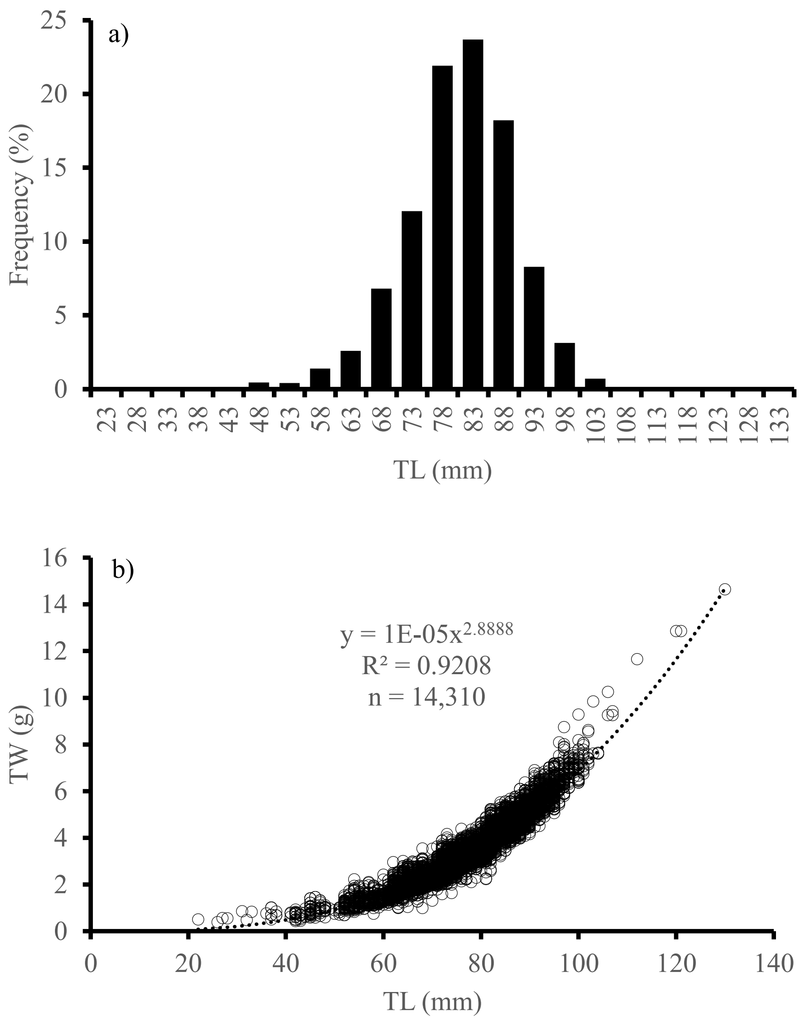


**Figure 2.** a) Population size structure and b) length-weight relationship of *Stolephorus commersonnii* from the ringnet fishery off the coast of Tanga during the 2016/2017 sampling season.

**Table 1.** Monthly variations in mean relative condition factors ($K_n$ ± s.d.) and mean growth coefficients ($b$ ± s.e.) with corresponding Student's $t$-tests for the cube law of *Stolephorus commersonnii* caught in ringnets off the coast of Tanga from August 2016 to August 2017 (*** = $p< 0.001$, ** = $p< 0.01$, * = $p< 0.05$ and NS = $p> 0.05$).

| Month | $K_n$ ± s.d. | $b$ ± s.e. | *df* | *t* | *p* | Remarks |
|---|---|---|---|---|---|---|
| Aug-16 | 1.21 ± 0.18 | 2.74 ± 0.03 | 1200 | -10.35 | *** | Allometric (-) |
| Sep-16 | 1.26 ± 0.21 | 2.53 ± 0.03 | 663 | -17.94 | *** | Allometric (-) |
| Oct-16 | 1.22 ± 0.13 | 2.93 ± 0.02 | 1053 | -2.85 | ** | Allometric (-) |
| Nov-16 | 1.18 ± 0.11 | 2.88 ± 0.02 | 1459 | -5.98 | *** | Allometric (-) |
| Dec-16 | 1.13 ± 0.09 | 3.03 ± 0.02 | 1143 | 1.67 | NS | Isometric |
| Jan-17 | 1.14 ± 0.15 | 2.88 ± 0.03 | 1151 | -4.39 | *** | Allometric (-) |
| Feb-17 | 1.16 ± 0.16 | 2.54 ± 0.03 | 984 | -13.83 | *** | Allometric (-) |
| Mar-17 | 1.15 ± 0.10 | 2.86 ± 0.02 | 1244 | -6.01 | *** | Allometric (-) |
| Apr-17 | 1.12 ± 0.10 | 3.11 ± 0.03 | 1125 | 3.93 | *** | Allometric (+) |
| May-17 | 1.12 ± 0.10 | 3.15 ± 0.03 | 1197 | 5.26 | *** | Allometric (+) |
| Jun-17 | 1.20 ± 0.22 | 2.92 ± 0.03 | 898 | -2.58 | * | Allometric (-) |
| Jul-17 | 1.20 ± 0.10 | 3.06 ± 0.02 | 1301 | 2.31 | * | Allometric (+) |
| Aug-17 | 1.18 ± 0.12 | 3.23 ± 0.03 | 866 | 7.49 | *** | Allometric (+) |
| Overall | 1.17 ± 0.01 | 2.89 ± 0.01 | 14308 | -16.07 | *** | Allometric (-) |

The growth parameters obtained for *S. commersonnii* were: asymptotic length ($L_\infty$) = 86.03 mm TL, instantaneous growth rate (K) = 1.19 per year, theoretical age at birth ($t_0$) = –0.01 years, and growth performance index (ϕ) = 3.9 (Fig. 3a). The longevity ($T_{max}$) of *S. commersonnii* was calculated at 2.5 years. The restructured length-frequency data superimposed with the estimated VBGF curves revealed that approximately three cohorts were sampled during the study period (Fig. 3b).

Total mortality (Z) was estimated at 1.39 $yr^{-1}$, natural mortality (M) at 0.86 $yr^{-1}$, and fishing mortality (F) at 0.53 $yr^{-1}$, being higher than optimum fishing mortality ($F_{opt}$ = 0.34 $yr^{-1}$). The current exploitation rate ($E_{cur}$) was estimated at 0.38 (Fig. 4a). The length-at-first capture ($L_{c50}$) of *S. commersonnii* was 40.51 mm TL with the corresponding capture at $L_{c25}$ and $L_{c75}$ 37.94 and 43.08 mm TL respectively (Fig. 4b). The length-at-first sexual maturity ($L_{m50}$) was 57.35 mm TL being higher than $L_{c50}$. Recruitment of *S. commersonnii* was noted to be year-round and bimodal, peaking in March and June/July (Fig. 5). Relative yield per recruit (Y'/R) and relative biomass per recruit (B'/R) are illustrated in Fig. 6a. The maximum relative yield-per recruit of *S. commersonnii* was achieved at the optimum exploitation rate of $E_{max}$ = 0.63. The exploitation rate at which the marginal increase of Y'/R is 10% of the virgin stock was $E_{0.1}$ = 0.56 and the exploitation rate where the stock is reduced by half of its virgin biomass was $E_{0.5}$ = 0.37. The yield isopleths from which the yield contours predicted the response of relative yield-per-recruit of the Commerson's anchovy to changes in $E_{max}$, $L_c/L_\infty$ and M/K are shown in Fig. 6b. Stock position of *S. commersonnii* within the investigated area fell at the edge in quadrant D of an overfished fishery with Y'/R corresponding to the 0.101 contour. The lowest Y'/R ($x$ = 0.017) could be obtained in quadrant A of an undeveloped fishery with values of $L_c/L_\infty$ = 1 and E = 0.1, whilst the highest Y'/R ($y$ = 0.161) was located in Quadrant C of a fully developed fishery with values of $L_c/L_\infty$ = 0.9 and E = 1.

## Discussion

The estimated monthly values of growth coefficients ('*b*') from the LWR model indicated that *S. commersonnii* exhibits an allometric growth pattern as observed for most anchovy species (Aripin and Showers, 2000; Abdurahiman *et al.*, 2004; Sag'lam and Sag'lam, 2013). These values were within the acceptable and expected range of between 2.5 and 3.5 which is typical for most tropical fish species (Froese, 2006). This notion is supported by the statement that an ideal fish with a '*b*' value of 3 is rarely observed in the natural environment (Allen, 1938). The Commerson's anchovy maintained a relative condition factor greater than a unit; an indication of individuals in

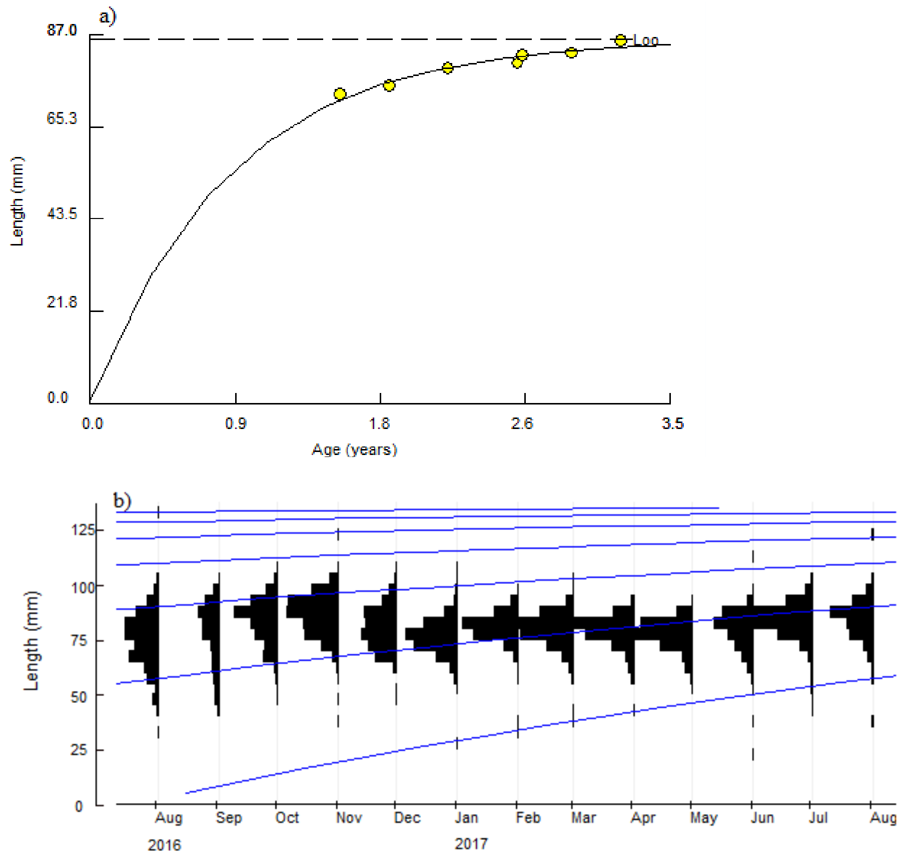


**Figure 3.** a) Length-at-age and b) von Bertalanffy growth function curves superimposed on restructured monthly length-frequency distributions of *Stolephorus commersonnii*.

good growth condition throughout the study period. The observed seasonal variation in relative condition factor was in agreement with other anchovies in the Black Sea (Sag'lam and Sag'lam, 2013). Preetha *et al.* (2015) suggested that variations in relative condition factor of the Commerson's anchovy in India might indicate the reactions of the fish populations to environmental changes, food abundance and spawning conditions affecting fish growth within the habitat. Higher $K_n$ values occurred during the northeast (NE) and southeast (SE) monsoons; an indication that both seasons support abundant food and possibly favouring a protracted spawning season for most of the anchovies by providing sufficient forage to sustain the energetic costs of repeated gonad maturation (Milton *et al.*, 1990). The lowest $K_n$ value in April/May might indicate a period of low reproductive activity or changes of environmental parameters associated with a high influx of freshwater and associated sediment load in the inshore water as a result of heavy rain (pers. obs.). The Commerson's anchovy is reported to be a coastal pelagic species that sometimes inhabits bays and estuarine habitats in Tanzania (Bianchi, 1985).

The present study is the first investigation on the population parameters of *S. commersonnii* off the coast of Tanzania. The Commerson's anchovy is a small pelagic fish (asymptotic length of 86 mm TL), with fast growing (instantaneous growth rate of 1.19 $yr^{-1}$ and growth performance index of 3.9). The species was also found to be short-lived, having a life expectancy of 2.5 years. These growth parameters are in agreement with published information for most of the anchovies studied in the Philippines (Ingles and Pauly, 1984). Worldwide studies on the population parameters of engraulids indicated that they are fast growing, short lived and have relatively high rates of natural mortality (Newberger and Houde, 1995). This is further supported by Arneril *et al.* (2011) who found that, particularly small pelagic fishes, have natural mortality rates which are often higher than fishing mortality rates. The results of the present study clearly reflect that *S. commersonnii* exhibited these characteristics.

The ratio of Z/K quantifies the relationship between growth and mortality. Etim *et al.* (1998) indicated that in populations where Z/K = 1, the mortality balances growth, Z/K< = 1 is growth-dominated, and Z/K = >1 is

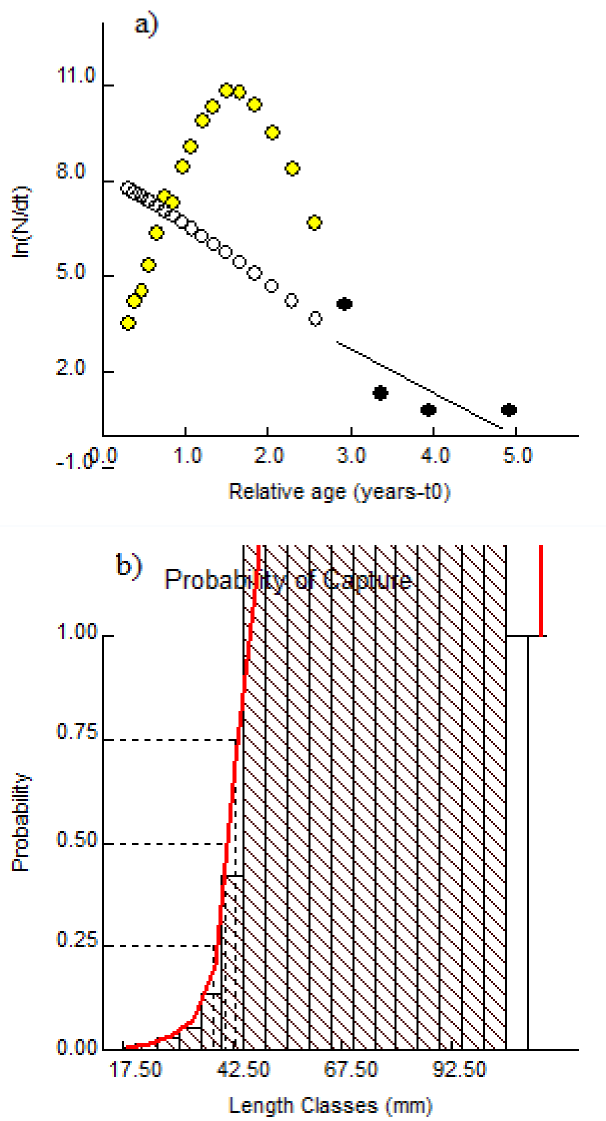


**Figure 4.** a) Length converted catch curve (solid dots = points used in calculating total mortality (Z) through least square linear regression analysis) and b) probability of capture of *Stolephorus commersonnii* at 0.25, 0.5 and 0.75 to estimate size-at-first capture.

mortality dominated. In this study, *S. commersonnii* exhibited Z/K = 1.15, an indication that the population is mortality dominated. This observation could be dependent on the density of predators with the species forming a major source of food for both pelagic and demersal fishes, marine mammals and seabirds (Bozzano *et al.*, 1997; Blanco *et al.*, 2001; Stergiou and Karpouzi, 2002) contributing to high natural mortality (M = 0.86 $yr^{-1}$). High fishing mortality (F) could be the result of intensive fishing pressure caused by small-mesh sized ringnets (8 – 10 mm) and about 1,126 and 1,184 fishers targeting small pelagics in Mkinga District and Tanga City respectively (MLF, 2016). Furthermore, the observed fishing mortality (F = 0.53 $yr^{-1}$) was higher than optimal fishing mortality ($F_{opt}$ = 0.34 $yr^{-1}$); an indication of a heavily exploited Commerson's anchovy population.

This contention is further supported by the fact that the length-at-first capture ($L_{c50}$ = 40.51 mm TL) was relatively lower than the length-at-first sexual maturity ($L_{m50}$ = 57.35 mm TL). The *S. commersonnii* fishery is therefore under the regime of catching smaller fishes at higher fishing effort; a condition termed growth overfishing. Moreover, the ratio of the length-at-first capture to the asymptotic length $L_{c50}/L_\infty$ = 0.47) suggests that younger fish constituted the catch of ringnets. The yield isopleths diagramme in this study placed the Commerson's anchovy stock at the edge of quadrant D, corresponding to the region of overfishing. Quadrant D has been referred to as a fishing regime where small fish are caught at high effort levels (Pauly and Soriano, 1986). Possible management interventions could include the introduction of harvest control rules such as an increase of mesh size of ringnets, restricting fishing during daytime and the spawning season, and limiting the number of fishers through fishing licenses. However, the suggested interventions require scientific data supported by a detailed stock assessment study.

The recruitment pattern observed in this study was year-round, though bimodal, conforming to the assertion by Pauly (1982) where two peaks of recruitment per year is a general feature of most tropical fish species. The current year-round recruitment pattern may be

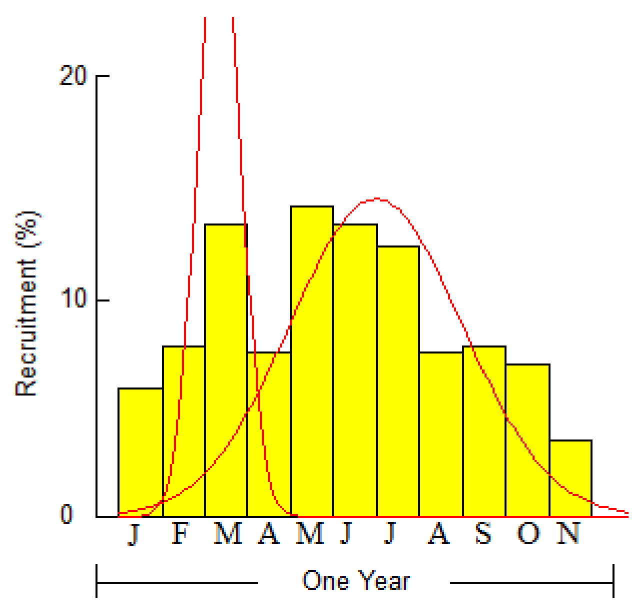


**Figure 5.** One-year recruitment pattern of *Stolephorus commersonnii* into the ringnet fishery off the northern coast of Tanga Region, Tanzania.

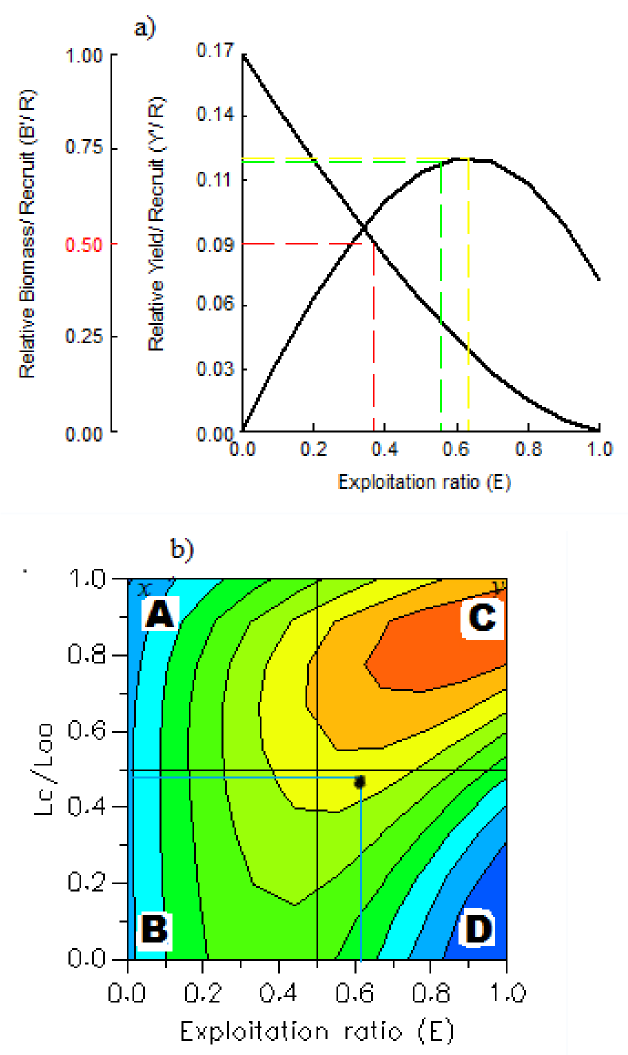


**Figure 6.** a) Relative yield per recruit (Y'/R) and relative biomass per recruit (B'/R) and b) yield isopleths diagram showing stock position of *Stolephorus commersonnii* placed at the edge of quadrant D fishing regime (A = under-fishing, B = developing fishery, C = fully developed fishery and D = over-fishing according to Pauly and Soriano (1986)).

an indication that the *S. commersonnii* fishery in Tanga Region is not suffering from recruitment failure, possibly offsetting the effects of overfishing reflected by its dominance in catches throughout the year (MLF, 2016). *S. commersonnii* conformed to the general observation that small pelagic fish species have a high turnover rate and are capable of withstanding high total mortality (Z) caused by fishing pressure (F) and natural mortality (M) due to predation pressure (Mannini, 1992).

The general productivity of a fish stock is determined by its life history pattern and its absolute abundance. This study has established that the Commerson's anchovy is a small, short-lived, pelagic, schooling fish often occurring in inshore waters, and most likely occupies a low trophic level. Furthermore, the year-round recruitment and fast growth to reach size-at-first sexual maturity is likely to attribute to the high turnover rate exhibited by *S. commersonnii*.

Based on this data-limited study, it is concluded that *S. commersonnii* off the northern coast of Tanga Region has a mortality dominated population under the regime of an overexploited fishery. For sustainability of the species management interventions are proposed leading to harvest control rules such as reducing fishing effort through licensing, increasing the mesh size of ringnets, restricting fishing during daytime, and introducing closed fishing seasons during peak spawning periods. It is further recommended that a stock assessment study is carried out that synthesizes information on life-history, and includes fishery monitoring and resource surveys for estimating stock size and harvest rate relative to sustainable reference points. The proposed stock assessment study should be aimed at providing advice on the optimum fishing effort that will produce the maximum sustainable yield in weight from the fish population, to ensure the well-being of Tanga coastal communities in the long term.

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## References

Abdurahiman KP, Harishnayak TP, Zacharia U, Mohamed KS (2004) Length-weight relationship of commercially important marine fishes and shellfishes of the southern coast of Karnataka, India. NAGA, WorldFish Center Quarterly 27: 9-14

Allen KR (1938) Some observations on the biology of the trout (*Salmo trutta*) in Windermere, Journal of Animal Ecology 7: 333-349

Aripin IE, Showers PAT (2000) Population parameters of small pelagic fishes caught off Tawi-Tawi, Philippines. NAGA, ICLARM Quarterly 23: 21-26

Arneril E, Carpil P, Donato F, Santojanni A (2011) Growth in small pelagic fishes and its implications in their population dynamics. Biologia Marina Mediterranea 18: 106-113

Barange M, Coetzee J, Takasuka A, Hill K, Gutierrez M, Oozeki Y, Van der Lingen C, Agostini V (2009) Habitat expansion and contraction in anchovy and sardine populations. Progress in Oceanography 83: 251-260

Bianchi G (1985) FAO species identification sheets for fishery purposes: Field guide to the commercial marine and brackish water species of Tanzania. Prepared and published with support to TCP/URT/4406 and FAO (FIRM) Regular Programme. Rome. 199 pp

Blanco C, Salomón O, Raga JA (2001) Diet of the bottlenose dolphin (*Tursiops truncatus*) in the western Mediterranean Sea. Journal of the Marine Biological Association of the United Kingdom 81: 1053-1058

Bodiguel C, Breuil C (2015) Report of the meeting on marine small pelagic fishery in the United Republic of Tanzania. SFFAO/2015/34, IOC-SmartFish Programme of the Indian Ocean Commission. FAO. Ebene, Mauritius. 90 pp

Bozzano A, Recasens L, Sartor P (1997) Diet of the European hake *Merluccius merluccius* (Pisces: Merluciidae) in the Western Mediterranean (Gulf of Lions). Scientia Marina 61: 1-8

Checkley DM Jr., Alheit J, Oozeki Y, Roy C (eds) (2009) Climate change and small pelagic fish. Cambridge University Press, Cambridge. 352 pp

Checkley DM Jr., Asch RG, Rykaczewski RR (2017) Climate, anchovy, and sardine. Annual Review of Marine Science 9: 469-493

Cole J, McGlade J (1998) Clupeoid population variability, the environment and satellite imagery in coastal upwelling systems. Reviews in Fish Biology and Fisheries 8: 445-471

Etim L, Sankare Y, Brey T, Arntz W (1998) The dynamics of unexploited population of *Corbula trionga* (Bivalvia: Corbulidae) in a brackish-water lagoon, Cote d'Ivoire. Archive of Fishery and Marine Research 46: 253-262

FAO (2016) The state of world fisheries and aquaculture 2016. Contributing to food security and nutrition for all. Rome. 200 pp

Fischer W, Bianchi G (eds) (1984) FAO species identification sheets for fishery purposes. Western Indian Ocean (Fishing Area 51). Danish International Development Agency (DANIDA)/Food and Agricultural Organization of the United Nations (FAO), Rome. Vol 1-6. pp var

Froese R (2006) Cube law, condition factor and length weight relationships: history, meta-analysis and recommendations. Journal of Applied Ichthyology 22: 241-253

Fujimoto, M (2018) Economic impact of the *dagaa* processing industry on a coastal village in Zanzibar, Tanzania. African Study Monographs, Suppliment 55: 145-162

Guénette S, Melvin G, Bundy A (2014) A review of the ecological role of forage fish and management strategies. Canadian Technical Report of Fisheries and Aquatic Sciences. 3065 pp

Gulland JA (1983) Fish stock assessment: a manual of basic methods. Wiley Interscience, Chichester, UK. FAO/ Wiley, Vol 1. 223 pp

Hoggarth DD, Abeyasekera S, Arthur RI, Beddington JR, Burn RW, Halls AS (2006) Stock assessment for fishery management: A framework guide to the stock assessment tools of the fisheries management science programme. Fisheries Technical Paper No 487. FAO. Rome. 261 pp

Ingles J, Pauly D (1984) An atlas of the growth, mortality and recruitment of Philippines fishes. ICLARM Technical Report 13. International Center for Living Aquatic Resources Management, Manila. 127 pp

Kawasaki T (1980) Fundamental relations among the selections of life-history in marine teleosts. Bulletin of the Japanese Society of Scientific Fisheries 46: 289-293

Le Cren ED (1951) The length–weight relationship and seasonal cycle in gonad weight and condition in the perch *Perca fluviatilis*. Journal of Animal Ecology 20: 201-219

Lindegren M, Checkley DM Jr., Rouyer T, MacCall AD, Stenseth NC (2013) Climate, fishing, and fluctuations of sardine and anchovy in the California Current. Proceedings of the National Academy of Sciences 110: 13672-13677

Lluch-Belda D, Crawford RJM, Kawasaki T, MacCall AD, Parish RH, Schwartlose RA, Smith PE (1989) World-wide fluctuations of sardine and anchovy stocks: the regime problem. South African Journal of Marine Sciences 8: 195-205

Mannini P (ed) (1992) The Lake Victoria "Dagaa" (*Rastrineobola argentea*). Report of the first meeting of the working group on Lake Victoria *Rastrineobola argentea*, 9–11 December, 1992, Kisumu, Kenya. UNDP/ FAO Regional Project for Inland Fisheries Planning (IFIP) RAF/87/099-TD/38/92

Milton DA, Blaber SJM, Tiroba G, Leqala J, Rawlison NJF, Hafiz A (1990) Reproductive biology of *Spratelloides delicatulus*, *S. gracilius* and *Stolephorus heterolobus* from the Solomon Islands and the Maldives. Australian Centre for International Agricultural Research Proceedings 30: 89-99

MLF (2016) Ministry of livestock and fisheries, fisheries development division: Marine fisheries frame survey 2016 Report. Mainland Tanzania. 84 pp

Munro JL, Pauly D (1983) A simple method for comparing the growth of fishes and invertebrates. ICLARM Fishbyte 1: 5-6

Newberger TA, Houde ED (1995) Population biology of bay anchovy in the mid-Chesapeake Bay. Marine Ecology Progress Series 116: 25-37

Pauly D (1979) Theory and management of tropical multispecies stocks: a review with emphasis on the Southern Asian demersal fisheries. ICLARM Studies and Review. Manila Vol 1. 35 pp

Pauly D (1980) On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. Journal du Conseil International pour l'Exploration de la Mer 39: 175-192

Pauly D (1982) Studying single-species dynamics in a multispecies context. In: Pauly D, Murphy GI (eds) Theory and management of tropical fisheries. ICLARM Conference Proceedings Vol 9. International Centre for Living Aquatic Resource Management, Manila. pp 33-70

Pauly D (1983) Some simple methods for the assessment of tropical fish stocks. FAO Fisheries Technical Paper Vol 234. 52 pp

Pauly D (1984) Fish population dynamics in tropical waters: a manual for use with programmable calculators. ICLARM Studies and Review. Manila Vol 8. 325 pp

Pauly D, Soriano ML (1986) Some practical extensions to Beverton and Holt's relative yield-per-recruit model. In: Maclean JL, Dizon LB, Hosillos LV (eds) The first Asian fisheries forum. Asian Fisheries Society, Manila. pp 491-496

Pitcher TJ (1995) The impact of pelagic fish behavior on fisheries. Scientia Marina 59: 295-306

Preetha GN, Joseph S, Pillai VN (2015) Length-weight relationship and relative condition factor of *Stolephorus commersonii* (Lacepède, 1803) exploited along Kerala coast. Journal of Marine Biological Association of India 57: 28-31

Sag'lam NE, Sag'lam C (2013) Age, growth and mortality of anchovy *Engraulis encrasicolus* in the south-eastern region of the Black Sea during the 2010–2011 fishing season. Journal of the Marine Biological Association of the United Kingdom 93: 2247-2255

Smith MM, Heemsta PC (eds) (2003) Smith's sea fishes. Struik Publishers, Cape Town. 1047 pp

Stergiou KI, Karpouzi V (2002) Feeding habits and trophic levels of Mediterranean fish. Reviews in Fish Biology and Fisheries 11: 217-254

Whitehead PJP, Nelson GJ, Wongratana T (1988) FAO species catalogue. Clupeoid fishes of the world (Suborder Clupeoidei). An annotated and illustrated catalogue of the herrings, sardines, pilchards, sprats, shads, anchovies and wolf-herrings. FAO Fisheries Synopsis 125 (7/2): 305-579

# Livelihood impacts and adaptation in fishing practices as a response to recent climatic changes in the upwelling region of the East African Coastal Current

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## Abstract

A socio-economic assessment was carried out at Amu and Shela in Lamu County and Ngomeni in Kilifi County on the coast of Kenya. The aim was to establish fisher perspectives on the livelihood impacts of changes in upwelling associated with the East African Coastal Current, and adaptations in fishing practices to determine the vulnerability, resilience and adaptation options for fisheries dependent communities in this upwelling region. Primary data and information were collected through direct observation, semi-structured interviews, key informant interviews and oral histories. Descriptive and non-parametric analysis was conducted for quantitative data and content analysis for qualitative data. The study covered 92 respondents out of which 90 were male. About 82.5 percent of the respondents had attained different levels of primary school education and below, and were therefore highly vulnerable to climate change impacts. Furthermore, 80.4 percent of the respondents were aged between 20 years and 49 years with a mean age of 40 years, thus falling into the economically active age category. In terms of livelihoods, fishing and fishing-related activities formed the primary livelihoods at the three study sites with fishing being the main occupation for 93 percent of the respondents. Fishing effort was higher during the north-east monsoon season. Fifty two percent of the respondents targeted small pelagic species. The main changes observed included increased fishing effort and a decline in the quantity of fish caught per fisher, and changes in the composition of fish species. Changes in the composition of fish species have further been compounded by a decline in rainfall over time, sea level rise, irregular wind patterns and increased temperatures. The decline in fish catch further led to a general decline in income and welfare. The climatic changes increased vulnerability of the fishing communities.

**Keywords:** Livelihood, Coastal communities, Small pelagic fish, Upwelling, Modern technologies, Descriptive statistics

## Introduction

Coastal upwelling is closely related to human welfare since it supports some of the most productive fisheries in the world. Upwelling is driven by alongshore wind stress through Ekman transport divergence at the coast, and by the nearshore wind stress curl through Ekman pumping (Miranda *et al.*, 2013). The flow turns to the right in the northern hemisphere and to the left in the southern hemisphere because of the Coriolis force. If that happens to be in an offshore direction, surface water moves offshore and is replaced by cold, nutrient-rich deeper water (Wang *et al.*, 2015) fueling phytoplankton blooms that feed higher trophic levels. Upwelling is associated with massive populations of small pelagic fishes such as sardines, anchovies, mackerels, threadfins and herrings (Bakun *et al.*, 1998; Bakun *et al.*, 2010). Coastal communities in the East African region have relied on the sea for livelihood and culture and have gained extensive experience on the conditions of their marine environment. They depend on the biological productivity which is induced by coastal upwelling and have learnt to adapt to a combination of the north-east monsoon (NEM) and south-east monsoon (SEM) winds, precipitation

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and tidal variation, which influences marine and land-based activities (Tobisson *et al*., 1998; Tobisson, 2014).

Coastal communities in Kenya depend on fisheries and other coastal resources for their livelihoods. The importance of fisheries as a livelihood is particularly pronounced in Lamu, Kilifi and Kwale Counties. Ruwa *et al*. (2003) observed that Lamu and Tana River Counties are endowed with a rich marine inshore fishery with the most productive fishing areas being the North Kenya Banks.High productivity in the North Kenya Banks is associated with upwelling. The increasing irregular patterns of wind and sea conditions caused by climate change is however diminishing peoples' ability to 'read nature' because of variable timing of winds and shifting seasons, rendering the people unable to make reliable predictions to time their activities as had been the case in the past (Lyimo *et al*., 2013).

Lack of timely and adequate information and the lack of improved technologies are influencing the quality of people's response options, often compelling them to engage in further biodiversity degradation. There is evidence that low adaptive capacity, which refers to the capacity of humans and institutions to adjust to potential damage to take advantage of opportunities or respond to consequences, is either leading to increased poverty because of low catches and diminishing capabilities to curtail risks (Yanda, 2013), or to competition and resource degradation, as fishers converge on those areas where resources are likely to be found, such as around reefs (Cinner *et al*., 2010).

Enhancing people's adaptive capacity and enabling them to anticipate and respond to changes, to minimize, cope with, and recover from the consequences of change (Cinner *et al*., 2011) is increasing the prospects of fisheries governance in the East African region (Yanda, 2013). Governance practices have also evolved overtime to respond to changing ecological conditions and the impacts of climate change, often for improved biodiversity protection, but also to promote community resilience and adaptive management (Yanda, 2013; Ruwa, 2011). The most recent ecosystem approaches to management as applied within Marine Parks and other biodiversity protection mechanisms are some of these responses. Yet, there is still evidence that management systems are unable to

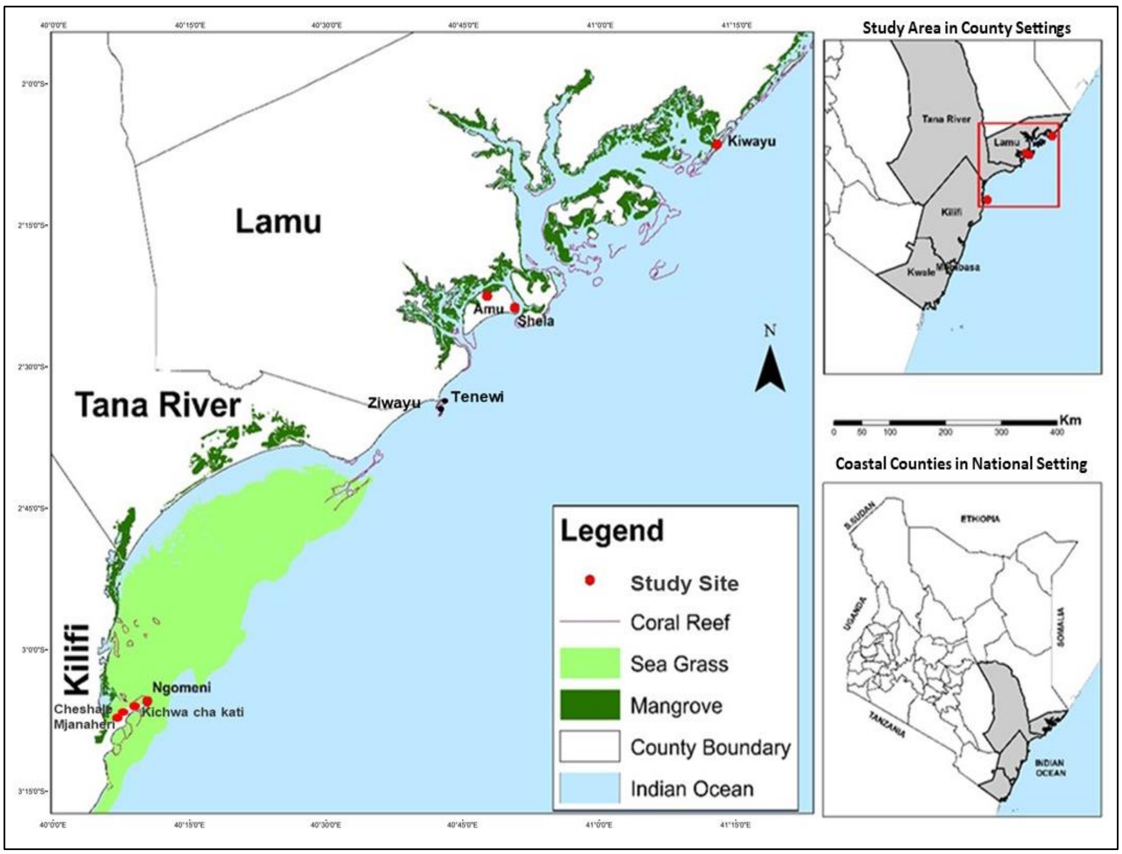


**Figure 1.** Map showing location of the study sites on the coast of Kenya.

enhance the predictive capacity of fisheries managers and the fishing communities, or respond to oceanic conditions induced by climate change (Ruwa, 2011).

The study sought to establish the social and economic impacts of changes in the upwelling driven by the East African Coastal Current (EACC) on livelihoods and adaptation of fishing practices. The EACC is the dominant surface current influencing East African coastal waters and is characterized by the interaction between the Southern Equatorial Current (SEC) and the African coastline bringing relatively cool water from the south. The EACC is accelerated during the SEM and slower during the NEM. It flows northward throughout the year at 4 knots between latitudes 11°S and 3°S (Newell, 1959; Swallow *et al*., 1991; Nguli, 2006). The specific objective of the study was to evaluate stakeholder perceptions on the impacts of climate change among fishing communities in the EACC upwelling region on the Kenya coast.

## Materials and Methods

### Study site

The study was carried out at Ngomeni in Kilifi County, and Amu and Shela in Lamu County on the coast of Kenya (Fig. 1). The three sites were selected based on existing knowledge and desktop reviews on communities that depend on the small pelagic fisheries around the area where upwelling occurs. The study covered three sites at Ngomeni namely Ngomeni village, Kichwa cha Kati and Cheshale. Ngomeni is situated approximately 16 kilometres north of Malindi town and is heavily dependent on fisheries as the main source of livelihood. The village has three categories of fishers; namely those who fish in the inshore areas, those who fish at the Malindi Bank and the North Kenya Bank, and migrant fishers who fish at distant fishing grounds such as Ziwayu in the Tana River Delta, and Tenewi and Kiwayu in Lamu County (Fig. 1).Like Ngomeni, Lamu depends on artisanal fishing as the main source of livelihood. Some of the fishers operate in the shallow inshore waters of the Lamu Archipelago while others occasionally fish at the North Kenya Banks which is located 30nautical miles offshore (Morgans, 1959; KMFRI, 2018).

## Methodology

Both quantitative and qualitative research approaches were used. The target population covered communities that engaged in fishing and fisheries related activities.Multi-stage sampling was adopted involving different techniques within each stage. Fishers were first stratified with respect to their target fishery which was categorized by fishing gears, and thereafter, samples were drawn purposively from each type of fishery. County Fisheries Directors, Beach Management Unit (BMU) officials and Village heads were also included in the ultimate sample in order to obtain perceptions of those engaged in fisheries governance. For oral histories and key informant interviews the study also targeted experienced artisanal fishers who had been fishing for over 10 years in areas influenced by upwelling.

Primary data and information were collected through direct observation, semi-structured interviews, key informant interviews and oral histories (Bunce *et al*., 2000; De la Torre-Castro *et al*., 2007). Direct observation involved examination of small pelagic fishery landings, the type of gears and boats used, sale transactions and other associated activities at the study sites. Semi-structured interviews were conducted with the fishers and community members that were engaged in fisheries related activities. It involved the use of a defined set of open-ended questions which allowed for the flexibility to probe deeper into issues and pursue new lines of questioning in order to generate information on specific issues of interest (Bunce *et al*., 2000). The questions covered demographic characteristics, information about the small pelagic fisheries, information about upwelling, types of fishing gears and vessels used, duration of fishing and landings, climate change and perceptions on future scenarios. Each interview lasted between 45 minutes and 1 hour. The interviews were conducted in Kiswahili, which is the spoken language that is commonly understood by all respondents. A total of 92 respondents (90 males and 2 females) were interviewed.

Key informant interviews were used to obtain particular information from selected opinion leaders who had unique knowledge about local livelihoods including fisheries and the upwelling conditions associated with the EACC. The selected key informants included the local Beach Management Unit (BMU) chairmen, local leaders such as chiefs and village heads, County Fisheries Officers and officers from the State Department of Fisheries, Aquaculture and Blue Economy (SDFA&BE),who provided insights on many issues that needed further clarification. Oral histories were used to get an in-depth account of personal experiences and reflections from key knowledge-holders, particularly elders, who recounted their historical experiences with respect to changes in climate and oceanographic conditions associated with upwelling, fishing practices including effort and catch trends, livelihoods and institutions. Information on fishing effort and catch trends were validated using the marine fisheries frame survey report for Kenya that is produced every two years and a national report on the status of Kenya's fisheries (Republic of Kenya, 2016; Kimani *et al.*, 2018). The elders were identified through snowball sampling which involved letting the local people identify the elders (De la Torre-Castro *et al.*, 2007). This helped to understand people's vulnerabilities and responses to changes over time.

The data analysis involved transcription of the datasheets into an excel worksheet, cleaning for entry errors, coding of variables and proof reading to correct any inconsistent codes. Exploratory analysis was then conducted to verify inconsistencies, anomalies, missing values and outliers using the Statistical Package for Social Sciences (SPSS). Descriptive analysis of the responses was undertaken, where mean, standard deviation, frequencies and percentages were computed. Non-parametric analysis was conducted to establish relationships between variables. Content analysis was conducted on the qualitative data in order to systematically evaluate responses and determine the emerging themes on the status of the small pelagic fishery and upwelling. The analysis involved synthesizing the qualitative data by investigating key concepts, emerging patterns and themes that seemed to dominate the findings.

## Results and Discussions

### Demographic Characteristics of the Respondents

Of the 92 people who were selected and available for the study, only 2 were female (Table 1).The dominance of male respondents is attributed to the fact that the study targeted people who were involved in fisheries as a livelihood source, most of whom were male. This is consistent with the findings by Ochiewo (2004) that traditionally, fishing is a male occupation and therefore any study that targets fishers is likely to have more male than female respondents. In terms of age, 80.4 percent of the respondents were aged between 20 years and 49 years (Table 1) with the average age being 40 years. This means that most of the fishers fell into the active age category and therefore had the energy required for fishing operations. In addition, about

**Table 1.** Demographic characteristics of the respondents in the study.

| Gender | Number | Percent |
|---|---|---|
| Male | 90 | 97.8 |
| Female | 2 | 2.2 |
| **Age** | | |
| 20-29 years | 21 | 22.8 |
| 30-39 years | 30 | 32.6 |
| 40-49 years | 23 | 25 |
| 50-59 years | 8 | 8.7 |
| 60-69 years | 10 | 10.9 |
| **Education level** | | |
| Complete primary | 22 | 23.9 |
| Complete secondary | 5 | 5.4 |
| Higher education | 3 | 3.3 |
| Incomplete primary | 30 | 32.6 |
| Incomplete secondary | 8 | 8.7 |
| Madrassa | 12 | 13.0 |
| No education | 12 | 13.0 |

41 percent of the respondents were aged between 40 years and 69 years and had therefore been involved in fishing for a long period. These respondents had gained valuable experience and observed changes that occurred in the small-pelagic fisheries as well as local climatic and oceanographic conditions over many years. About 23 percent of the respondents were aged 20 years to 29 years indicating that young people are also being recruited to the small pelagic fishery.

Most respondents had low levels of education with 13 percent having no education at all, 32.6 percent had incomplete primary level of education, 13 percent had basic Islamic education (Madrassa), and 23.9 percent had a primary school certificate (Table 1). This implies that about 82.5 percent of the respondents had attained different levels of primary school education and below and were therefore highly vulnerable to climate change impacts based on vulnerability indicators by Colburn *et al.*(2016). Only 8.7 percent of the respondents had attained secondary and higher education and were therefore more resilient as they could access alternative livelihoods.

### Livelihood Sources

Fishing and fishing-related activities including fish trading constituted the primary livelihoods at the three study sites. Fishing was the primary occupation for most (94.6 percent) of the respondents followed by fish trading (5.4 percent). While fishing was traditionally a male occupation (Ochiewo, 2004), a few women particularly at Ngomeni had turned to fishing as their preferred livelihood. Fish trade on the other hand was carried out by both men and women. Men had relatively more capital and therefore operated as fish dealers with deep-freezers and fish shops while women operated on a smaller scale as fishmongers, who bought small quantities of fish from the fish landing sites, processed the fish through deep-frying and sold it in the villages and local market centres. The three study sites, Ngomeni, Amu and Shela are typical fishing villages among several other typical fishing villages spread across Lamu and Kilifi Counties, thus confirming the importance of fisheries as a source of livelihood. The importance of fishing and other fisheries-related activities has also been elaborated by the County Government of Lamu (2018). Secondary

**Table 2.**Common small pelagic fish landed at Lamu and Ngomeni, based on responses.

| Small Pelagic Fish | Scientific name | Family name | Common/English name | Percentage of small pelagic fish catch |
|---|---|---|---|---|
| Una/oona | *Rastrelliger kanagurta* | Scombridae | Indian mackerel | 18.18% |
| Simu/kerenge | *Sardinella melanura* | Clupeidae | Blacktip sardinella | 16.23% |
| Mkizi | *Mugil cephalus* | Mugilidae | Flathead grey mullet | 12.34% |
| Pangapanga | *Pterogymnus laniarius* | Sparidae | Panga seabream | 8.44% |
| Mtumbuu | *Strongylura leiura* | Belonidae | Banded needlefish | 7.14% |
| Mbinini | *Planiliza alata* | Mugilidae | Diamond mullet | 6.49% |
| Nyimbwi | *Albula vulpes* | Albulidae | Bonefish | 3.90% |
| Mkeke/chuchungi | *Hemiramphus lutkei* | Hemiramphidae | Lutke's halfbeak | 3.25% |
| Peruperu | *Monodactylus falciformis* | Monodactylidae | Full moony | 3.25% |
| Chuchungi/mkeke | *Hemiramphus far* | Hemiramphidae | Black-barred halfbeak | 1.30% |
| Mamba ngumu | *Hypoatherina barnesi* | Atherinidae | Barnes' silverside | 0.65% |
| **Others** | | | | |
| Bonito | *Sarda orientalis* | Scombridae | Striped bonito | 9.09% |
| Kisumba | *Sphyraena barracuda* | Sphyraenidae | Great barracuda | 4.54% |
| Sehewa | *Euthynnus affinis* | Scombridae | Kawakawa | 1.30% |
| Sehewa | *Katsuwonus pelamis* | Scombridae | Skipjack tuna | 3.90% |

livelihood sources included sand harvesting which is widely practiced in the area between Ngomeni and Mjanaheri. The harvested sand was transported by tracks to Malindi and Mombasa where it is used as building material. Small scale businesses also constitute another important livelihood source particularly at Ngomeni where there were several retail shops selling groceries, and temporary kiosks which sell food, fruit and vegetables. Peasant farming was also practiced by the fisher households at Ngomeni as an alternative livelihood. The crops grown by the fisher households were mainly coconut and sesame.

## Target species

Based on the responses, the common small pelagic fish landed and traded were Indian mackerel which constituted 18.2 percent of the total catch, sardines that accounted for 16 percent of the total catch, mullets (12.3 percent of the catch), ribbonfish (8.4 percent of the catch), banded needlefish (7.1 percent of the catch), common blue stripe snapper, diamond mullet and mackerels (Table 2).The results are consistent with the findings by Munga *et al.* (2016) and Kimani *et al.* (2018) that the most common small pelagic species landed by ringnets in Kenya include *Stolephorus delicatulus*, *Harengula humeralis*, and *Sardinella gibbosa*; while medium pelagic species include *Hemiramphus far, Rasterlliger kanagurta,* and the barracudas *Sphyraenajello, Sphyraenaflavicauda,* and *Sphyraenaobtusata*. Seventy seven percent of the fishers did not target small pelagic fish, but caught them as by-catch of the demersal fishery.

## Fishing effort

Seine nets (both ringnets and reef seines), cast nets, gillnets, harpoons, fence traps, scoop nets, longlines and monofilament nets are the main fishing gears used in the small pelagic fishery. Sardines were targeted by the ringnets, cast nets and reef seines. The ringnets targeted different species based on the time of fishing, the net mesh sizes and the area of deployment. The ring nets deployed during the day target reef and pelagic species while those deployed at night mainly target sardines. While 45 percent of the 38 ringnets in Kenya target sardines (Republic of Kenya, 2016), the three ringnets that were in operation at Ngomeni targeted the small and medium pelagic species.

Cast net were used to target prawns (82 percent), sardines (16 percent) and other species (2 percent). Cast nets were mainly bell-shaped gillnets tied to a rope held by the fisher, and were thrown out over the water to spread out and land on the surface, thereafter sinking to the bottom, entrapping fish when retrieved. The cast nets were only found at Ngomeni in Kilifi County with none observed in Amu and Shela in Lamu County. Reef seines were seine nets operated within the reefs and operated by two crafts. The reef seines targeted sardines (6 percent) alongside non-pelagic fish species such as scavengers (21 percent), rabbit fishes (16 percent), and snappers (10 percent). The study established that a few of the scoop nets targeted sardines (2 percent). However, scoop nets were mainly used as accompanying fishing gears by divers who targeted lobsters (77 percent), aquarium fish (10 percent), and crabs (9 percent).The findings are consistent with the observation by Kimani *et al.* (2018) that small pelagic species typically aggregate and are often caught using surrounding fishing gears such as small-scale purse seines which are commonly referred to at ringnets.

Mullets were targeted by gillnets of single vertical panels of below 3 inches mesh size which were either set or active. Harpoons, fence traps, scoop nets and longlines with some longline hooks that were set at the surface were also used. The harpoons targeted octopus (67 percent) and mullets and scavengers (13 percent). About 42 percent of the fence traps targeted prawns while 10 percent targeted mullets and the remainder targeted grunters (18 percent) and carangids (16 percent). Longlines were defined as a single twine on which a series of short branch lines were attached at intervals. A baited hook is attached at the end of each short branch line which can be of various sizes, and the longline is anchored in the deep waters to fish. In Lamu County the number of hooks increased by 115% from 2,165 in 2014 to 4,659 in 2016 (Republic of Kenya, 2016).

Most of the fishing vessels that were sampled at Ngomeni, Amu and Shela where small pelagic species were targeted, were modern motorized fiber boats. These boats were popular with the fishers who target small and medium pelagic fish that require traveling long distances to access their preferred fishing grounds. Less than 50 percent of the fishers in Kenya target small pelagic species because Kenya's coast is endowed with demersal stocks that are exploited by over 50 percent of the fishers, despite being threatened by over-fishing. Most of the fishers who target demersal fish relied heavily on sailboats, wooden planked boats, traditional dug-out canoes and fibre boats. Data from Kenya's marine artisanal fisheries frame survey of 2016 shows that the sail boats (popularly known as *mashua*) were the most dominant fishing vessel in

Lamu County accounting for 48 percent of all fishing vessels. The frame survey data further showed that the traditional dugout canoe was the dominant fishing vessel in Kilifi County accounting for 68 percent of all the fishing vessels. Despite the threat of overfishing on the demersal stocks in the seagrass beds and coral reefs in Kenya, a larger number of artisanal fishers target demersal stocks compared to small pelagic stocks. Consequently, most of the artisanal fishers fish within the coral reef where they do not have to travel long distances. The sailboats were also preferred by a section of the respondents (29.6 percent) because they rely on wind and are therefore cheaper to operate compared to the modern motorized fibre boats that require fuel to be purchased. The sailboats had a carrying capacity of 3 to 4 crew members and most of them were owned by individual entrepreneurs who employed the crew to work for them.

Approximately 49 percent of respondents reported that the small pelagic fish were mainly caught during the NEM season while the rest stated that they were also caught during the SEM season (27.2 percent), both seasons (21.7 percent) and during the inter-monsoon period (2.2 percent).A Chi-square test for independence indicated an association between fishing effort and availability of small pelagic fish across seasons ($X^2_{(9,\ n=92)}$ =0.292, p=0.005, phi=0.506).The p value is less than 0.05 implying that there was a statistical relationship between the variables.

The study sought to establish the time (number of days and hours) fishing is carried out during both the NEM and SEM seasons and these results are presented in Table 3. Time spent fishing was analyzed because it is determined by the target fishery and it is an important measure of fishing effort. In terms of target fishery, the small purse seine (ring net) is used at night to target sardines and anchovies and is used during the day to target both reef and pelagic species. Previous studies such as Ochiewo (2004) also indicated that time is a measure of fishing effort with fishers spending more hours in the sea during the calm NEM season and less hours during the SEM season. The results showed that fishing was conducted for 5.62 days per week during the NEM season. This means that fishers went fishing for 6 days in each week and rested for one day, mainly on Friday which is the main prayer day for Muslims. On average fishing duration has increased over time from 6 hours per day during the NEM season 30 years ago to 8 hours per day in 2018. In the past, artisanal fishers never travelled long distances to fish at the North Kenya Banks or the Malindi Bank that require a 24 hour trip, because they caught enough fish within the inshore areas. During the SEM, fishing is conducted for 5 days per week. The number of hours spent fishing during the SEM season has also increased from 4 hours per day 30 years ago to 6 hours per day during the current study. Overall, the number of hours spent fishing has increased over time. Further, there was less fishing effort during the SEM season compared to the NEM season. The SEM season coincides with strong winds and rough seas. During this time, most fishing activities take place within the sheltered shallow inshore areas which can be accessed using small fishing crafts.

### Fish preservation

The results in Table 4 reveal that 48.5 percent of the small pelagic fish was sold fresh to the buyer/consumer, 33.8 percent of the fishers used ice to preserve their catch of small pelagics, while others used other methods of preservation, including salting and drying (16.2 percent), deep freezers and deep frying.

The majority (52.1%) of the respondents targeted small pelagic species which are used as bait as well as for food. The small pelagic species were considered seasonal, were easily caught at night and could be found

Table 3. Descriptive statistics for fishing time during the NEM and SEM seasons.

| Season | Fishing time | N | Minimum | Maximum | Mean (±SD) |
|---|---|---|---|---|---|
| NEM | Fishing days per week | 85 | 2 | 7 | 5.62±1.3 |
| | Fishing hours per day | 80 | 1 | 24 | 8.39±5.3 |
| SEM | Fishing days per week | 81 | 1 | 7 | 4.91±1.7 |
| | Fishing hours per day | 81 | 2 | 24 | 5.81±3.4 |

Table 4. Frequency distribution of fish preservation methods for small pelagic fish.

| Fish preservation method | N | Percent |
|---|---|---|
| Preservation in ice | 23 | 33.8 |
| Selling while fresh | 33 | 48.5 |
| Salting and sun-drying | 11 | 16.2 |
| Deep frying | 1 | 1.5 |
| Total | 68 | 100 |

near shore. The respondents observed that the small pelagic fish provided high income compared to demersal fish because they are caught in large quantities and have a ready market. It was noted that there were some fishers who did not target the small pelagic fish but captured these fish incidentally.

### Knowledge and perceptions of the impacts of upwelling

About 52 percent of the respondents did not have a particular term for the upwelling phenomenon and could not confirm that they fished around the upwelling areas. However, 42 percent of the respondents described the phenomenon and explained how they interacted with it through their fishing activities. They described upwelling uniformly elaborating on aspects such as water in the upwelling area being relatively cooler compared to water outside the upwelling area. The level of disparity in knowledge about upwelling could be attributed to the fact that upwelling took place in the distant deeper waters and only those fishers who travelled to the upwelling area could observe it. Further, one needs to be observant in order to recognize the phenomenon and therefore it was only those fishers who were keen to observe the physical characteristics of their fishing grounds were able to recognize it. When asked about the period when upwelling occurs, about 30 percent of the respondents stated that they were not aware. The study also revealed that 40 percent of the respondents did not recognize the importance of upwelling.

Changes in fishing practices and scenarios of change

The study sought to examine both short-term and long-term changes in fishing practices. It was established that long-term changes experienced included increased use of motorised vessels/boats, changes in type of fishing gears used with the introduction of 2 ringnets at Ngomeni, increased crew size from the traditional crew of 2 for gillnets to a crew of 4 for monofilament nets, and a crew of 23 to 31 for ringnets, increased time spent fishing at sea, changing fishing grounds and increased number of fishers. The increased fishing effort caused a decline in the quantity of fish caught per fisher and changes in the composition of fish species, with some species becoming very rare. The decline in fish catch led to a general decline in income, which has translated to a decline in welfare, and the fishers have become worse off today than 30 years ago. To counter these changes, the communities opted to adopt alternative livelihoods.

The key informants observed that climatic changes such as a decline in rainfall over time, irregular wind patterns and increased temperatures have impacted negatively on small pelagic fish landings. About 60 percent of the respondents did not have any idea of the changes that occur in the upwelling areas and therefore they were not able to describe their effects. When asked about changes that have occurred in the fishing grounds, about 31 percent of the respondents stated that over the past 5-10years a decline in the fish catch had been observed due to bad weather, increased temperatures, increased winds/turbulence, effect of brine from the salt pans, changing weather conditions, dredging of the Lamu port that has polluted the sea, use of destructive fishing gears, influx of fishers, lack of rain and the inability of fishers to venture offshore.

The perceptions on the scenarios of future changes were diverse(Table 5).Approximately 57 percent of the respondents observed that if a shift in the sites where pelagic fish are mostly caught occurred, this will result in reduced catch. Consequently, 38 percent of the fishers said they will respond by venturing into the non-traditional fishing grounds in the offshore waters while 28 percent said they were likely to change their fishing grounds within the inshore areas where they currently operate. In addition, the respondents observed that if a 50 percent reduction in the small pelagic fish stocks

Table 5. Perceptions on the likely effects and responses to future scenarios of climate change.

| Scenario of change | Likely effect | Frequency | Per-centage | Likely response | Response Frequency | Per-centage |
|---|---|---|---|---|---|---|
| A shift in the sites where pelagic fish are mostly caught | Reduced catch | 43 | 56.6% | Increase effort | 10 | 12.2% |
| | Increased fishing effort/time | 17 | 22.4% | Change fishing ground | 23 | 28.0% |
| | Increased operational cost | 7 | 9.2% | Change target fishery | 2 | 2.4% |
| | Loss of income | 5 | 6.6% | Opt for alternative Livelihood | 1 | 1.2% |
| | None | 4 | 5.3% | Opt for alternative gear, fish,bait | 5 | 6.1% |
| | | | | Venture offshore | 31 | 37.8% |
| | | | | None | 10 | 12.2% |
| | Total | 76 | 100.0% | **Total** | **82** | **100.0%** |
| A reduction of the small pelagic fish stocks by half (50%) | Reduced catch and income | 54 | 71.1% | Venture offshore | 2 | 2.6% |
| | Food insecurity | 8 | 10.5% | Change fishing ground | 8 | 10.4% |
| | Lack of preferred fish type | 2 | 2.6% | Change target fishery | 19 | 24.7% |
| | Decreased fish population | 1 | 1.3% | Change fishing gear | 4 | 5.2% |
| | Scarcity of bait | 1 | 1.3% | Increase effort | 8 | 10.4% |
| | Disruption of the food chain | 1 | 1.3% | Opt for alternative livelihood | 17 | 22.0% |
| | Reduced trade | 1 | 1.3% | None | 19 | 24.7% |
| | None | 8 | 10.5% | | | |
| | Total | 76 | 100.0% | **Total** | **77** | **100.0%** |
| A reduction of the small pelagic fish catch by half (50%) | Reduced catch and income | 63 | 84.0% | Change target fishery | 8 | 11.8% |
| | Reduced trade | 4 | 5.3% | Increase effort | 8 | 17.7% |
| | Harder to get bait | 1 | 1.3% | Change fishing ground | 5 | 7.4% |
| | Disruption of the food chain | 1 | 1.3% | Look for alternative bait | 2 | 2.9% |
| | None | 6 | 8.0% | Government intervention | 2 | 2.9% |
| | | | | Opt for alternative livelihood | 33 | 48.5% |
| | | | | None | 6 | 8.8% |
| | **Total** | **75** | **100.0%** | **Total** | **68** | **100.0%** |

**Table 6.** Desired changes and the means to achieve them as identified by the respondents.

| First priority | Means of achieving the desired changes |
|---|---|
| 1. Adoption of modern technology in fishing | 1. Advocate provision of proper gear and advanced vessels to venture offshore |
| 2. Removal of fish landing fees | 2. Stakeholders engagement |
| 3. Ban on illegal fishing gears | 3. Strengthen co-management between government institution and BMU |
| 4. Strengthening of co-management and inclusive management strategies/approaches | 4. Adherence to laws and regulations and promotion of surveillance |
| 5. Conservation of the environment by halting the dredging of Lamu port | 5. Identify better markets for fish |
| 6. Controlling pollution that caused the migration of fishers | 6. Allocate adequate budget |
| 7. Empowerment of fishers with vessels and equipment (introduction of new fishing technology)to venture into deep sea fishing | 7. Develop a compensation mechanism for the construction of port since it has negatively impacted the fishing grounds |
| 8. Frequent surveillance and monitoring of fishing operations | 8. Ban beach seine in the channels |
| 9. Limiting fishing effort to allow sustainable use of these fisheries resources | |
| 10.Need to empower the BMU | |

occurred, it may lead to reduced catch, decreased income and food insecurity. If the negative impacts are realized, about 25 percent of the respondents said they will change their target fishery, 22 percent will opt for alternative livelihoods, 10 percent will change fishing ground and 10 percent will increase effort over time while 25 percent were not committed to any of the options. Further, the respondents observed that if a reduction of the small pelagic fish catch by half (50 percent) occurred, it may lead to reduced income to fishers. The fishers said they are likely to respond to this change scenario by opting for alternative livelihoods (about 49 percent), changing the target fishery (12 percent), increasing their fishing effort (12 percent), and changing their fishing grounds (7 percent).

The respondents identified the desired changes as well as the means to realize these changes and results(Table 6).The desired changes can be categorized into three themes, namely, modernization of fishing technology and empowerment of fishers to enable them to increase their catches and income by venturing offshore, elimination of illegal fishing gears by strengthening surveillance and monitoring of fishing operations and stakeholder engagement, and strengthening of co-management and conservation of the environment. It is anticipated that the desired changes will lead to increased income of the fishers, sustainable harvesting of small pelagic fisheries, and community participation in the management of pelagic fisheries.

## Conclusions

Fishing was the main occupation for 95 percent of the respondents from the 3 typical fishing villages. The importance of fishing as a source of livelihood, income and animal protein has been recognized in the County Integrated Development Plans for both Kilifi and Lamu Counties. Besides the 3 typical fishing villages that were studied, there are several other fishing villages spread across the two counties. Since this study has confirmed the importance of fishing as a main occupation in the two counties, attention should be paid to the sustainable development of fisheries so that fishers can have an assured source of livelihood. Less than 50 percent of the fishers target the small pelagic fishery. The fishing effort is higher in the small pelagic fishery during the NEM season which is associated with upwelling and calm sea conditions than in the SEM season when the sea is rough.

A number of changes have occurred in the climatic and oceanographic conditions that negatively impacted on pelagic fisheries. These changes included changes in rainfall patterns, sea level rise, irregular wind patterns and increased temperatures. The changes compounded the effects of increased fishing pressure and resulted in declining fish catch that further translated into decreased income from the small pelagic fisheries. The fishers have responded by adopting the use of motorised vessels/boats to enable them travel further to access distant fishing grounds such as the

North Kenya Bank, changing the type of fishing gears used including introduction of small-purse seine nets (ringnets), increasing crew size, and increasing time spent fishing at sea.

Supporting interventions that will enable the primary school population to successfully transition to secondary and tertiary levels of education or training will equip the youth with skills to minimize their vulnerability and build resilience to climate change impacts. The skills gained from secondary education and training will enable more people to access alternative livelihoods.

Three categories of desired changes in fisher empowerment and fisheries governance issues were identified by respondents, namely modernization of fishing technology to enable fishers to increase their catches and income by venturing offshore, elimination of illegal fishing gears by strengthening surveillance and monitoring of fishing operations and stakeholder engagement, and strengthening of co-management and conservation of the environment. The fishers anticipate that the desired changes will lead to improved livelihoods and income, enhanced adaptive capacity to climate change, sustainable harvesting of small pelagic fisheries, and enhanced community participation in the management of pelagic fisheries. Overall, some of the initiatives that have been identified to address climate change impacts include incorporating climate change in planning activities to develop instruments that provide a combination of adaptation and mitigation measures that are effective over time and space, ensuring that mitigation measures are implemented by various players, undertaking capacity building at all levels through training, education and awareness creation, and ensuring rational use and protection of small pelagic fisheries resources by eliminating destructive fishing practices and regulating fishing effort. This may further involve altering catch size, protecting the breeding grounds, and reducing the level of fishing effort to sustain yields.

## Recommendations

There is a need to implement both government and traditional rules that target the management of the small pelagic fishery in the area. Issues such as compliance and enforcement of rules and regulations and discouraging the use of destructive fishing gears like monofilament nets need to be addressed. Furthermore, deliberate efforts to introduce alternative livelihoods to assist the fishers are necessary. Both Government and Non-Governmental Organizations should join hands to support education and training to build the capacity of fisher communities and equip them with skills to enable them access alternative livelihoods, minimize their vulnerability and build their resilience to climate change impacts. The support could include protecting the primary and secondary school population against social problems such as child labour, drug abuse and early marriages.

## References

Bakun A, Field D.B, Redondo-Rodriguez A, Weeks S.J (2010) Greenhouse gas, upwelling-favorable winds, and the future of coastal ocean upwelling ecosystems. Global Change Biology. 16: pp. 1213-1228

Bakun A, Roy C, Lluch-Cota S (1998) Coastal upwelling and other processes regulating ecosystem productivity and fish production in the western Indian Ocean. In: Okemwa E, Ntiba M, Sherman K (eds) Large Marine Ecosystems of the Indian Ocean: Assessment, Sustainability, and Management. Malden: Blackwell Science. pp 103-141

Bunce L, Townsley P, Pomery R, Pollnac R (2000) Socioeconomic manual for coral reef management. Australian Institute of Marine Science. pp 92-168

Cinner JE, McClanahan TR, Graham NAJ, Daw TM,Maina J, Stead SM, Wamukota A, Brown K, Bodin O (2011) Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. Global Environmental Change 22(1):12-20

Cinner JE, Mcclanahan TR,Wamukota A (2010). Differences in Livelihoods, Socioeconomic Characteristics, and Knowledge About the Sea Between Fishers and Non-fishers Living Near and Far from Marine Parks on the Kenyan Coast. Marine Policy. 34: pp22-28.

Colburn LL, Jepson M, Weng C, Seara T, Weiss J, Hare JA (2016) Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf coasts of the United States. Marine Policy 74:pp323-333

County Government of Lamu (2018) Lamu County Integrated Development Plan 2018 – 2022. County Government of Lamu, Lamu, Kenya. 353 pp

De la Torre-Castro M, Ochiewo J, Mbaga TK, Pinault M (2007) A framework for addressing socioeconomic and management aspects of sea cucumber resources in the Western Indian Ocean. SPC Beche-de-mer Information Bulletin 25:pp22-28

Kimani EN, Aura MC, Okemwa GM (eds) (2018) The status of Kenya fisheries: Towards the sustainable exploitation of fisheries resources for food security and economic development. Kenya Marine and Fisheries Research Institute (KMFRI), Mombasa. 135 pp

KMFRI (2018) The RV Mtafiti: Marine research towards food security and economic development for Kenya. Njiru JM, Ruwa RK, Kimani EN, Ong'anda HO, Okemwa GM, Osore MK (eds). Kenya Marine and Fisheries Institute, Mombasa, Kenya. 102pp

Lyimo J, Ngana J, Liwenga E, Maganga F (2013) Climate change impacts and adaptation on the coastal communities in Bagamoyo District, Tanzania. Environmental Economics 4(1):63-71

Miranda PM, Alves JM, Serra N (2013) Climate change and upwelling: response of Iberian upwelling to atmospheric forcing in a regional climate scenario. Climate Dynamics 40 (11-12):2813-2824

Morgans JFC (1959) The North Kenya Banks. Nature, London 184:259-260

Munga CN, Okemwa GM, Kimani EN, Wambiji N, Aura CM, Maina GW, Manyala JO (2016) Stock assessment of small and medium pelagics: Status of ringnet and reef seine fisheries along the Kenyan coast, KCDP Project. KMFRI Technical Report. Mombasa, Kenya. 42pp

Newell BS (1959) The hydrography of the East African coastal waters. Fishery Publication 9.Her Majesty's Stationery Office, London

Nguli MM (2006) Water exchange and circulation in selected Kenyan creeks. PhD Dissertation. Earth Science Centre, University of Dar es Salaam, C78 2006

Republic of Kenya (2016) Marine artisanal fisheries frame survey 2016 report. Ministry of Agriculture Livestock and Fisheries, State Department of Fisheries, Kenya. 97pp

Ruwa RK (2011)Policy and governance assessment of coastal and marine resource sectors in Kenya in the framework of Large Marine Ecosystems. Report to the ASCLME Policy and Governance Coordinator, ASCLME Project, Grahamstown, South Africa. 58pp

Ruwa R, Habib G, Mukira M, Okoth G, Mwatha G (2003) Profile of Kenya Marine and fisheries: Country Working Resource Document. GEF-South-West Indian Ocean Fisheries Project (SWIOFP) in Kenya. Publication No. 1 (2003). 71 pp

Ochiewo J (2004) Changing fisheries practices and their socioeconomic implications in South Coast Kenya. Ocean and Coastal Management 47: 389-408

Swallow JC, Scott. F, Fieux M (1991) Structure and transport of the East African Coastal Currents. Journal of Geophysical Research 96: 22,245-22,257

Tobisson E, Andersson J, Ngazi Z, Rydberg L, Cederlöf U (1998) Tides, monsoons and seabed: Local knowledge and practice in Chwaka Bay, Zanzibar. Ambio 27: 677-685

Tobisson E (2014)Consequences and challenges of tourism and seaweed farming: A narrative on a coastal community in Zanzibar. Western Indian Ocean Journal of Marine Science 12(2):169-184

Wang D, Gouhier TC, Menge BA, Ganguly AR (2015) Intensification and spatial homogenization of coastal upwelling under climate change. Nature, London 518: 390-394

Yanda PZ (2013) Coastal and marine ecosystems in a changing climate: The case of Tanzania, Climate Change Adaptation Series: Document 1. Coastal Resources Center, University of Rhode Island, Narragansett, RI. 21 pp

# Appendix – Questionnaire

## Masma Project:

**Responses of Biological Productivity and Fisheries to Changes in Atmospheric and Oceanographic Conditions in the Upwelling Region Associated With the East African Coastal Current (*EACC*)**

Location ______________________________ Date: ___/____/ 2016

### Part I. Personal Information

1. Name of respondent (optional) ______________________________
2. Residence ______________________________
3. Sex of respondent: Male (   ) Female (   )
4. Age(yrs): ______________________________
5. Education level (Tick where applicable): No education (1), Incomplete primary (2), Complete primary (3), Incomplete secondary (4), Completed Secondary (5), Higher education (6), Madrassa (7), Other (please specify) (8)

   ______________________________
6. Main occupation of respondent: ______________________________

## Part II: Understanding of pelagic fisheries productivity and ocean upwelling

*To begin, we are interested in your knowledge of a particular type of fishery. There are no right or wrong answers, we'd just like to learn more about your experiences.*

### Pelagic Fisheries

7. When I talk of fish that live in the middle of the water, not on the bottom and not on the reef, do you know what I mean? Do you have a name for this group of fish? __________

8. We are most interested in those fish that are small even when fully grown. Can you give me the local names for these kinds of fish? **Use fish pictures to prompt here.* __________

9. What do you know about these fish? **Prompt (a-c)*

   a. What time of the year do you find them most? __________

   b. What conditions make for more fish? __________

   c. What factors cause these fish to decline? __________

10. Do you target these fish in your fishing activities? Why / why not? __________

11. Who normally does target this type of fish? __________

### Upwelling

12. When you go to sea, how far out in the sea do you go? __________

13. Are there areas in the ocean where sometimes surface water is pulled down into the deep water, or where deep water rises to the surface? Do you have a name for this?**Use upwelling / downwelling pictures to prompt here.*

   a. How do you know / can you see when water from the deep rises to the surface? **Prompt, cold water, turbulence, lots of fish* __________

   b. Where does it occur? __________

   c. When is it strongest? __________

   d. Do you know why / how this occurs? __________

14. Is the ocean upwelling important to you in any way? __________

15. Do you fish in the upwelling area? Why / why not? __________

16. Are there people from your village who fish in the upwelling area? Who? __________

17. Do you know of any connections between climate, upwelling and fisheries? Can you describe the relationship among them? __________

## Part III: Fishing / Marine Practices

Fishermen

| | NEM* (Nov – Apr) | | SEM (May – Oct) | |
|---|---|---|---|---|
| 18. What type of gear(s) do you use each season? Do you own your gear? *List in order of most used. Indicate ownership in brackets. (Self, Shared, Hired, Employer's)* | E.g., Line (Self) | | | |
| | 1. | | | |
| | 2. | | | |
| 19. What type of vessel do you use each season? Vessel ownership, size (m/ft), propulsion, and crew number? *List in order of most used. Indicate ownership, size, propulsion, crew in brackets.* | E.g., Ngalawa (Employer's, 3m, wind, 2 crew) | | | |
| | 1. | | | |
| | 2. | | | |
| a. How often do you fish in each season? *Days/wk + hrs/day* | Days/wk ______ | hrs/day______ | Days/wk______ | hrs/day______ |
| 20. How much fish do you land by species on average (kgs per day for **top three** target species)? | E.g., Kingfish (5 kgs/day) | | | |
| | 1. | | | |
| | 2. | | | |
| | 3. | | | |
| a. How much small pelagic fish do you land by species, if not in top 3 species (kgs per day for **top three** species)? | 1. | | | |
| | 2. | | | |
| | 3. | | | |
| b. At what price do you sell these fish? *Price/kg* | 1. | | | |
| | 2. | | | |
| | 3. | | | |
| 21. Where do you fish for small pelagics? *Provide local name of fishing ground and list in order of importance.* | 1. | | | |
| | 2. | | | |
| | 3. | | | |
| a. Why do you choose these areas to fish small pelagics? *Please explain* | | | | |

22. How do you process/preserve your small pelagic fish catch? ______

23. How much of these fish do you consume on average (Kg/day)? ______

    a. How much of your small pelagic catch do you keep to consume? ______

    b. How much small pelagic fish do you purchase? ______

24. What do you do with any pelagic catch that you don't eat / sell? ______

## Non-fishers

25. What type of fish do you mostly purchase for consumption? ______

    a. How much fish does your household consume on average (Kg/day)? ______

    b. If at all, how much small pelagic fish do you purchase for food? ______

26. What type of fish do you mostly purchase for trade? ______

    a. (b) How much fish do you purchase for trade on average (Kg/day)? ______

    b. (c) If at all, how much small pelagic fish do you purchase for trade on average (Kg/day)? ______

    c. (d) How do you process / preserve this pelagic fish? ______

    d. (e) At what price is this pelagic fish sold? ______

    e. (f) Who do you sell to and where? ______

27. If at all, how often do you go to sea? ______

## Part IV: Vulnerability and adaptation of the fisher communities in the EACC upwelling region in relation to climate change

Experiences of change

| | Recent changes (5-10 yrs) | Longer term changes (10+ yrs) |
|---|---|---|
| 28. Have you observed changes in weather patterns, winds, rains, sea temperatures or sea levels i) over the last 5-10 years ii) over the longer term (10+ yrs)? *Please describe these changes* Do you have a name for these changes? | | |
| a. How have these recent and long termchanges affected you, if at all? | | |
| 29. Have you noticed any changes in upwelling (e.g., location, strength, timing)i) over the last 5-10 years ii) over the longer term (10+ yrs)? *Please describe these changes* | | |
| a. (b) How have these recent and long termchanges affected you, if at all? | | |
| b. (c)How do you respond to these recent and long-term changes in weather and oceanographic conditions? | | |
| c. (d)How have your responses improved your life or minimisedany negative impacts on your life, if at all? | | |
| 30. Have you observed any changes in your fishing grounds or the oceani) over the last 5-10 years ii) over the longer term (10+ yrs)?*Please describe these changes* | | |
| a. In your opinion, what caused these changes? *List top three causes in order of importance.* | 1. | |
| | 2. | |
| | 3. | |

| | Recent changes (5-10 yrs) | Longer term changes (10+ yrs) |
|---|---|---|
| 31. Have you observed any major changes in your small pelagic fish catches or what you can purchase (e.g., catch size, composition) i) over the last 5-10 years ii) over the longer term (10+ yrs)? *Please describe these changes* | | |
| a. In your opinion, what caused these changes? *List top three causes in order of importance.* | 1. | |
| | 2. | |
| | 3. | |
| b. How have these recent and long term changes affected you, if at all? | | |
| 32. Have you changed your fishing/trading practices i) over the last 5-10 years ii) over the longer term (10+ yrs)? *Please describe these changes* | | |
| a. What are your top three reasons for changing your practices? *List top threereasons in order of importance.* | 1. | |
| | 2. | |
| | 3. | |
| b. How have thesechanges improved your life or minimisedany negative impacts on your life, if at all? | | |
| 33. Have your household changed the way they make a living i) over the last five years ii) over the longer term? *Please describe these changes* | | |
| a. What are your household's top three reasons for doing so? *List top threereasons in order of importance* | 1. | |
| | 2. | |
| | 3. | |
| b. How have thesechanges improved your life or minimisedany negative impacts on your life, if at all? | | |

## Scenarios of change

34. In your opinion, **if** you experienced the following changes in future how would they affect you and how would you most likely respond?

   a. A shift in the time when pelagic fish are plentiful.
   Affect ______________________ Response ______________________

   b. A shift in the location of where pelagic fish are mostly caught (e.g., further offshore).
   Affect ______________________ Response ______________________

   c. A reduction by half (50%) of the number of small pelagic fish in the ocean. **Prompt impacts on large pelagics*
   Affect ______________________ Response ______________________

   d. A reduction by half (50%) of your small pelagic catch.
   Affect ______________________ Response ______________________

## Risk communication and early warnings

35. From who do you receive information on the weather and climate? *List* ***top three*** *sources (E.g., community elders, scientists, fisheries department. Be as precise a possible.)*

   1. ______________________
   2. ______________________
   3. ______________________

   a. How do you receive this information? *List* ***top three*** *media for knowledge exchange (E.g., meetings, mobile phone, radio, newspaper. Be as precise a possible – ie. Name newspaper)*?

      1. ______________________
      2 ______________________
      3. ______________________

   b. What sort of information do you receive? ______________________

   c. How useful do you find this information?*Extremely useful (1), very useful (2), 50:50 (3), not very useful (4), not at all useful (5). Please rank.* ______________________

36. From who do you receive information on pelagic fish? *List* ***top three*** *sources (E.g., community elders, scientists, fisheries department.Be as precise a possible.)*

   1 ______________________
   2. ______________________
   3. ______________________

   a. How do you receive this information? *List* ***top three*** *media for knowledge exchange (E.g., meetings, mobile phone, radio, newspaper. Be as precise a possible – ie. Name newspaper)*?

      1. ______________________
      2. ______________________
      3. ______________________

   b. What sort of information do you receive? ______________________

   c. How useful do you find this information? *Extremely useful (1), very useful (2), 50:50 (3), not very useful (4), not at all useful (5). Please rank.* ______________________

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## Part V: Governance institutions for small pelagic fisheries

37. Is anyone prevented from catching small pelagic fish? *Please explain why / why not*?

________________________________________

38. What government regulations apply to pelagic fishing or the people who catch pelagic fish? (E.g., gear bans, licenses). *Please list* ***top three***.

    1. ______________________________
    2. ______________________________
    3. ______________________________

    a. Do you agree or disagree that these government regulations are acceptable to people? *Strongly disagree (1), disagree (2) neutral (3), agree (4), strongly agree (5).*

    b. To what extent do fishers comply with these government regulations? *Completely (1), mostly (2), 50:50 (3), slightly (4), not at all (5).*

    1. __________ Acceptable __________ Comply __________
    2. __________ Acceptable __________ Comply __________
    3. __________ Acceptable __________ Comply __________

39. What traditional or local rules apply to pelagic fishing or the people who catch pelagic fish? (E.g., taboos, landing fees, trade tax). *Please list* ***top three.***

    1. ______________________________
    2. ______________________________
    3. ______________________________

    a. Do you agree or disagree that these local rules are acceptable to people? *Strongly disagree (1), disagree (2) neutral (3), agree (4), strongly agree (5).*

    b. To what extent do fishers comply with these local rules? *Completely (1), mostly (2), 50:50 (3), slightly (4), not at all (5).*

    1. __________ Acceptable __________ Comply __________
    2. __________ Acceptable __________ Comply __________
    3. __________ Acceptable __________ Comply __________

40. How do the rules and management of these fish change with the seasons, if at all? *Please explain*

________________________________________

41. How have the rules and management of these fish changed over the years, if at all? *Please explain*
In what ways are you involved in how your community manages these fisheries? *List* ***top threee***

    1. ______________________________
    2. ______________________________
    3. ______________________________

42. In what ways are you involved in how government manages these fisheries? *List **top three***
    1. __________
    2. __________
    3. __________

43. Please rank your agreement or disagreement with the following statements. *Strongly agree (1), agree (2) neutral (3), disagree (4), strongly disagree (5)*

    a. I am able to influence the important decisionsmade about the small pelagic fishery. __________

    b. The organisations managing the small pelagic fishery are accountable to the people that depend on this fishery. __________

    c. The organisations managing the small pelagic fishery are able to respond appropriately to changing circumstances whether environmental, social or political. __________

    d. The small pelagic fisheries are effectively managed? __________

44. Knowing what you know about this fishery what would you change about how it is managed? List in order of priority:
    1. __________
    2. __________
    3. __________

    a. How could these improvements happen? __________

45. Any other comments __________

## The End

Thank you for your time.

**Interviewers name:** __________

**Date** __________

# Adaptive capacity of small pelagic fishing communities in coastal Tanga (Tanzania) to changes in climate-related phenomena

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## Abstract

Studies examining the vulnerability, resilience and adaptation options of fisheries-dependent coastal communities have noted a decrease in viable options to respond effectively to the impacts of climate change. The extent of vulnerability is experienced in terms of varying capacity to respond to ecological changes through resource use practices. We analyzed the experiences of three coastal communities dependent on small pelagic fisheries in Tanga region, Tanzania, and their responses to the changing availability of fisheries resources. The study illustrates how conditions associated with upwelling, while not readily obvious to fishers, match some of their fishing strategies, with implications for fisheries-dependent livelihoods. Yet, the fishers' perceptions are key determinants of the response options they adopt. Limited access to scientific knowledge also constrains the effectiveness of their response options. Our findings have important implications for the manner in which local and scientific knowledge systems can be integrated, particularly with regards to enhancing the adaptive capacities of coastal fishing communities through knowledge sharing.

**Keywords:** Sources of livelihood, Perceptions, Adaptive capacity, Small pelagic fishes, Climate change

## Introduction

One of the most significant factors associated with the vulnerabilities of coastal fisheries-dependent communities to ecological changes effected by climate change, is their inadequate adaptive capacity (Cinner *et al.*, 2012; Islam *et al.*, 2014; Koya *et al.*, 2017). This is due to their inability to effectively reconcile livelihood practices with current patterns of ecological changes (Daw *et al.*, 2009). Climate change, and the conditions associated to upwelling have been found to have multiple biophysical and social ramifications on coastal fisheries, with consequent implications on food security and employment (Lam *et al.*, 2012; Miller, 2014).

Upwelling along the coast of Tanzania occurs during the northeast monsoon (Valera *et al.*, 2015). During that period, the prevailing surface winds consistently blow from the north and with the effect of the Coriolis force, the surface water along the coast is pushed offshore. The water beneath, which is relatively rich in nutrients, then comes to the surface to replace the volume of water that has been moved offshore, and these waters accelerate productivity. Thus, coastal upwelling is often associated with increased productivity of both primary producers and small pelagic fishes. Conversely, during the southeast monsoon which occurs from April to October, the winds blow from the south and push the surface water from offshore towards the coast. This surface water, which is brought to the coast from offshore is poor in nutrients, and upon reaching the coast, pushes the rich bottom water offshore, thus decreasing the productivity

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of both primary producers and small pelagics. The objective of this study was to examine the knowledge, understanding, experiences and responses of fishers and fishing communities to these conditions associated with upwelling and the implications to their livelihood endeavours.

The likelihood that the seasonal changes in productivity in the small pelagic fisheries resources may have had some implications on the livelihoods of coastal communities is high, but not well established. For example, changes in the distribution and abundance of small pelagic fishes have been noted as a possible outcome of the effects of weather variability on the ocean (Faleiro *et al.*, 2016). These changes may be species specific (Klutse and Nunoo, 2016). In contexts where the small pelagic fishery is an important aspect of community livelihoods, the impact of these changes will indeed affect these communities and expose them to livelihood vulnerabilities (Anderson and Samoilys, 2016). Such vulnerabilities are magnified by over-reliance on the fisheries, increasing pressure on the fisheries, but spreading the risks even further (Daw *et al.*, 2009). Limited options in limited environments ultimately disrupt the sustainable availability of fishes, household protein supply and distribution of revenue from the fisheries sector (Lam, *et al.*, 2012). The social aspects of vulnerabilities to climate change and upwelling in this regard can further be captured in terms of the varying levels of risk that different population groups within the fisheries-dependent communities become exposed to, owing to their different social status in terms of gender, age, main occupation and ability to draw on other resources (Islam, *et al.*, 2014; Burton and Cutter, 2008).

Effective adaptive capacity in this regard can be influenced by several factors. Sometimes, it is the result of how population groups firstly perceive the causes of their risk, and are then able to take advantage of existing and emerging opportunities in response to the resulting biophysical and social disruptions affecting their sources of livelihood. These responses are noted to be in the form of various behavioural, social, organizational and technological mechanisms (Adger, 2006; Cinner *et al.*, 2012; Adewale, 2014). People's perceptions on the factors leading to changes in the fisheries, and hence their vulnerability, is thus a crucial determinant on the adaptation choices that they make (Katikiro, 2014). There is however, inadequate appreciation on the relationship between perceptions of risk to the adaptive choices taken by fisheries-dependent communities, such as those within small pelagic fisheries, and their response to upwelling conditions (Anderson and Andrew, 2016).

Some studies adopt the asset-based livelihood approach and delineate the varying inadequacies in requisite assets as contributing to vulnerability (Cinner *et al.*, 2009; Islam *et al.*, 2014). While such understanding is critical for examining adaptive capacities of fisheries-dependent communities, coastal people's tradition of '*reading the sea*' and their ageless engagement with it for livelihoods and culture, and a knowledge which has equipped them with adequate experience on the conditions of their natural environment, has facilitated taking advantage of biological productivity such as those induced by upwelling conditions in particular (Tobisson *et al.*, 1998; Nirmale *et al.*, 2007). This knowledge is however sometimes taken for granted, and is increasingly becoming more complex in the context of climatic changes (Shyam *et al.*, 2015). Increasing irregularity of weather patterns is making predictions difficult, diminishing the effectiveness of traditional responses to livelihood engagements. Cheung (2015) has asserted that it is even more difficult for people to relate traditional livelihood patterns to the changing conditions associated with upwelling. Understanding local perceptions on such complexities and how people adapt is thus an important contribution to knowledge (Perry and Sumaila, 2007).

The vulnerabilities that coastal fisheries-dependent communities face may also be aggravated by institutional ineffectiveness, particularly fisheries management systems which are meant to support artisanal and small-scale fisheries in dealing with changing sea conditions. Inadequate and untimely information systems on weather changes, or poor sharing of scientific information on upwelling locations (Shirley *et al.*, 2012) are examples. Fishers also harbour discontent with these institutions, seeing most as geared towards revenue collection and uninterested in supporting them in the context of climate change. The fisheries thus continue to be exploited in more or less traditional patterns with varying levels of success.

Inadequate comprehension of the intensity or magnitude of the threat arising from changing sea conditions may also influence the nature of adaptation responses (Forster *et al.*, 2013), and fishers are likely to persist within the confines of their traditional livelihood systems, weaving themselves into prevailing uncertainties. Oliver-Smith (2009) notes the prevailing uncertainty in such situations is "both at the level of physical impacts and at the level of responses to adaptations in human communities". This uncertainty has sometimes been the basis for extended exposure to vulnerable situations with long term consequences. Uncertainty can be generated by conflicting messages between perceptions on change and experience of change, especially where people cannot clearly give witness to physical changes in the marine environment. Such issues are not well captured in studies on the social implications of climate change-related conditions on coastal fisheries-dependent communities.

At the same time, it is also difficult to delineate how people and their complex relationships with local fisheries systems may respond to change. Social dynamism, new ideas and new experiences may open up varying adaptation possibilities for certain population groups within the same fisheries, albeit short-lived. Yet, studies on adaptive capacity have not often captured these possibilities and their implications in both their positive and negative dimensions. Likewise, plausible options such as re-organization of the corresponding fisheries value chain as adaptation from risk are not well articulated, giving indications of a gap in knowledge.

The objective of this study was to examine factors influencing the adaptive capacity of three fisheries-dependent communities in coastal Tanzania, associated with their perceptions and experiences of the effects of upwelling conditions on the local small pelagic fishery. The study analyses community livelihoods by interrogating how these communities (i) perceive and relate the causes of changes in the availability of small pelagic fishes to upwelling related conditions, (ii) the implications such perceptions have on their livelihood choices, and (iii) their perceptions of the choices they make to adapt to these changes.

## Materials and methods

### The study area

This study was conducted between April and December 2017 in coastal fishing communities around three landing sites in Tanga region, north-eastern Tanzania (Fig. 1). These were Kasera (Sahare, Tanga Municipality), Vyeru (Monga-Vyeru village, Mkinga District) and Petukiza (Zingibari village, Mkinga District). These sites were selected due to predominant use in the small pelagic fisheries in the region, which since 2010 has become increasingly important in the small pelagic fish trade.

Kasera landing site along the Sahare coast (see Fig. 1), is an urban location within Tanga Municipality. Municipal authorities estimated that about 70% of Tanga municipal residents depend on Kasera landing site for fish consumption and trade (pers. comm.). Kasera is also the main market for small pelagic fish in Tanga. The Sahare fishing grounds are under the jurisdiction of the Tanga Coelacanth Marine Park, which provides an added management intervention for the local fisheries. The other two sites, Vyeru and Petukiza, are rural sites in Mkinga District, located in the north of Tanga Municipality, about 20 and 40 km by road respectively from Tanga City along the Tanga-Horohoro highway. Data on the number of fishers and vessels at the landing from 2017 showed that Kasera had 1,501 fishers and 171 craft, and Vyeru had 750 fishers and 50 craft. Estimates for Kasera and Vyeru were drawn from a rough figure of 15-45 fishers per boat (in good seasons Mashua carry up to 45 fishers per fishing trip). Estimates for Petukiza of 2,118 fishers and 311 craft refer to 2016.

### Data collection and analysis

A combination of qualitative and quantitative techniques was used to examine the livelihood impacts and adaptive capacities of these communities in response to upwelling related conditions. A structured questionnaire was used to collect comprehensive data to map the pattern of livelihood activities in the fisheries, vulnerabilities and adaptation strategies. Eightyeight fishers were purposively selected from the landing site registers at Kasera and Vyeru, and fishers from Petukiza were selected by the local Beach Management Unit (BMU). The selection targeted both skippers (*nahodha*) and crew members in order to capture different experiences with the sea. Observations were also conducted to visualize the pattern of community engagements with the fisheries. In addition, in each community, Focus Group Discussions (FGDs) and In-depth Interviews (IDI) with women, long-time and retired fishers were conducted, including discussions with other stakeholders with fisheries management responsibilities. The discussions examined their interpretations of the nature of social dynamics influenced by changing fisheries and the implications to adaptive capacity.

To investigate how fishers communicated about ocean upwelling, diagrams of the process and ensuing sea conditions were used as visual guides to generate discussions. Visual guides were used because upwelling has no known terminology in the local language (Swahili) used by the fishers. Community vulnerabilities were assessed in relation to the following indicators: (i) experience and perceptions of factors leading to changing fisheries in the long and short term; (ii) implications of livelihood dependence on small pelagic fisheries; and (iii) adaptive capacity to these changes.

fish from the boats (porters), fish processing, boiling and drying particularly sardines (*dagaa)*, and retailing cooked food (mama lishe). Small-scale farming is practiced by both men and women. Full time farmers are mostly elderly (30%), retired from fishing and related employment, while other community mem-

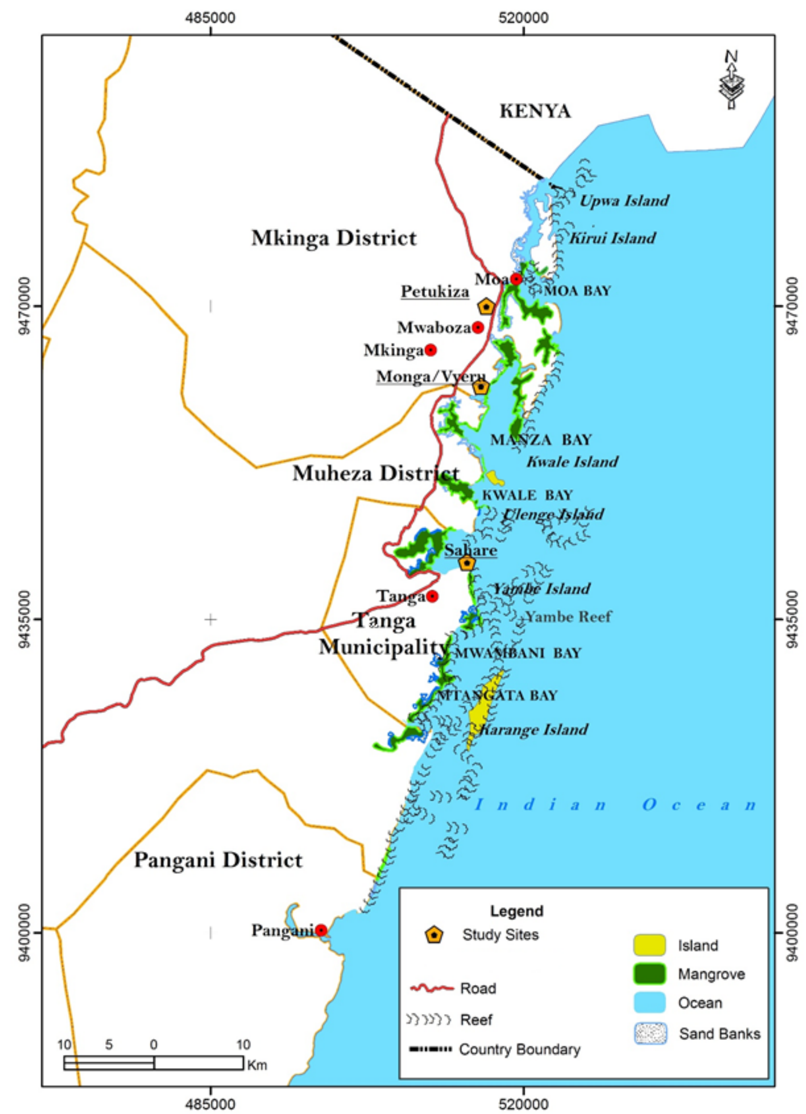


**Figure 1.** Map of Tanga Region, north east Tanzania, showing the study sites of Sahare, Vyeru and Petukiza (Source: Julitha Ipopo, IRA-UDSM, December, 2017).

## Results

### Community characteristics

In all communities, about 90% of the men were found to be engaged almost entirely in fishing and fish-related businesses. Men around Kasera enjoyed several other options, given its urban location and access to more employment or business opportunities. Women engaged in what are perceived as petty trades such as fish mongering, off-loading of bers would engage periodically in farming during off-fishing seasons.

During the study it was established that most of the fishers had basic literacy skills, 50% had completed primary school education, and 11% of them had completed secondary education. Only 8% had not received any formal education, and 13% did not complete primary education. The fishers however explained that they do not only undergo classroom-based education. They also go through informal apprenticeship, such as in fishing net mending and sea experience through fishing. Hence, the ability to read and write was not the primary means through which they are were enabled to cope with the sea.

Knowledge about the sea and fishing was shared among the fishers through word of mouth or by cellphones, and this system was important and effective in preparing them for their encounter with the sea. Fishers were of different ages and from different places of domicile. About 20% of the fishers mentioned that they have relocated from other locations to Tanga, especially from the islands of Pemba and Unguja in Zanzibar, and the rest were local to the fishing villages. Together, they had encountered a wide variety of experiences of the sea. Seasonal or local migrant fishers, mostly from the two islands, visited Tanga especially during the February-April and August-November fishing seasons. They set up camps (*dago*) near the shore according to a customary arrangement of accommodating migrant fishers in respective fishing villages. The timing of these visits was estimated to coincide with the end of each rainy period. Long-term experience in fishing among seasoned or migrant fishers was most relevant to the fishers' ability to 'read the sea', and this experience was evoked when discussing upwelling, climate change and small pelagic fisheries.

## Upwelling conditions and the fisheries

In order to determine the links between upwelling-related conditions, the prevalence of small pelagic fishes, and hence people's livelihoods, the study examined fishers' conceptualization of upwelling as a phenomenon. It was observed that the conditions associated with upwelling were communicated from two different positions; as an actual experience, and to upwelling as a perception of a certain phenomenon. Old-time fishers, as well as including divers who had been beneath the surface, were able to account confidently about changing sea temperature conditions. Other fishers gave accounts of changes in wave strength that they perceived influenced changes in sea water conditions - changes which they understood to have implications for productivity in the fisheries. Two conditions indicating such changes were mentioned: (i) changes in sea water conditions; and (ii) changes in the availability of small pelagic fish.

### *Changes in sea water conditions*

Changes in sea water conditions were categorized as changes in sea water temperature, and changes in the quality of sea water. Each change was seen to be a function of the changes in the weather seasons, and associated changes in temperature, strength or direction of the winds, and rainfall patterns. These sea conditions or phenomenon were named in a variety of ways (Table 1).

*(i) Sea water temperature*

Fishers also mentioned that they had experienced changes in water temperature with a general increase in temperature over the last few decades. Referring to the techniques or catching small pelagics, whereby a diver usually goes under the surface to set fishing nets, a long-term fishing skipper from the islands who is also a diver said, "during the past, it was very cold in the sea when one goes out fishing, especially at night". Fishers used to use heavy clothing during fishing trips to keep warm.

Fishers who are also divers explained that during the NE monsoons they experienced different levels of

**Table 1.** Fishers' local terms for changes in sea water conditions.

| Local term/reference of condition | Frequency | Percent |
|---|---|---|
| **Rainwater run off (*Mumbu*)** | 35 | 39.8 |
| No specific name | 27 | 30.7 |
| Cold temperature | 8 | 9.1 |
| Changes in the water quality | 8 | 9.1 |
| Curling water (*tububwe/danguliani/mboji*) | 6 | 6.4 |
| **Spring tide (*bamvua*)** | 3 | 3.4 |
| High sea surface temperature | 1 | 1.1 |
| Total | 88 | 100 |

sea temperature. A fisher explained that sometimes, the deeper one went, the colder it became from the warmer surface level water, giving an impression of the sea having different layers. Another diver-fisher further explained that during the NE monsoons, they may experience the water column as stratified into two or three layers of temperature. The number of layers can change from one year to another.

Adding to this, another fisher claimed that "nowadays, the sea is relatively warmer and the type of coldness that existed at night in the past is not felt anymore. Generally, fishers felt that the sea is becoming warmer for longer periods, and that, not only has the sea become warmer in the recent past, but they claimed that the air above the sea has warmed as well.

*(ii) Quality of sea water*

Fishers explained that the NE monsoons bring heavy rains which cause runoff from inland which also carry sediment and debris that pollute the water, locally known as *mumbu*. During the NE monsoon, water becomes "dusty", scouring debris, sand, broken corals, seagrass and all other bottom materials and thus the season "cleans" the ocean. *Mumbu* is regarded as unproductive for a certain period because it disturbs the quality of the water. However, this disturbance was considered as temporary, because fishers claimed that after a short period, the sea becomes quite productive. Scientifically, runoff from inland bring terrestrial nutrients to the coast by rivers which settle on the bottom. These can then be brought to the surface by upwelling and hence increase surface productivity. The aftermath of heavy rains is mostly favoured for fishing because of the understanding that the disturbance of the water brings nutrients up to the surface which attract fish leading to abundant catches. Fishers in Vyeru, for example, recalled how they experienced heavy rains for a whole day in May 2016. But "*after one week, we were able to harvest bangra at its boom at our local fishing grounds*" (FGD with fishers, Vyeru, 29/10/2017).

During the SE monsoon, the fishers mentioned that the sea was said to be a bluish colour and the inshore waters become very clear, which was relatively unproductive as compared to the disturbed water accompanying the NE monsoons.

### Causes of changing sea water conditions

Fishers' perceived that changing sea water conditions were a result of weather changes influenced by the monsoon winds, including the changing patterns of wind strength.

*(i) Weather conditions*

Weather related factors were explained in terms of changing patterns of wind strength and temperature. Such experiences were acknowledged as climate change (*mabadiliko ya tabia nchi*). Climate change was expressed in terms of unpredictable changes in rainfall patterns (24%) and changes in wind strength (21.5%). About 24% of the fisher respondents also mentioned that other changes that signified climate change included changes in the timing of spring tidal cycles (*bamvua)* and in the monsoon seasons and their accompanying conditions. For example, very heavy rains for short periods were said to cause a drastic disturbance in fishing patterns, inhibiting access to fishing grounds because of safety and impaired visibility, and also disturbing the marine environment.

*(ii) Timing of wind strength*

Generally, wind strengths were said to not have changed much, but people's predictions on the timing and strength of the winds was increasingly unreliable. Nevertheless, according to the fishers, stronger wings were still experienced during the SE monsoons than in the NE monsoons. Moreover, wind strength was associated with disturbances in the sea and ultimately to sea water conditions. Although wind force was said to be stronger during the SE monsoon, fishers believed that wave action did not penetrate down to the bottom and only affected the surface with no impact on fishing.

*(iii) Strength of sea waves*

Fishers also explained that during the NE monsoon "powerful waves" penetrated the entire water column, from the surface to the bottom, and fishing became difficult. According to fishers, this was the period of "turbulence". In contrast, during the SE monsoon, wave action was only felt at the surface – the force of waves did not reach the bottom. However, it was said that some inshore debris on the bottom was taken offshore by the "current" at this time.

## The small pelagic fisheries in Tanga

*Uono ndio habari ya mjini!* (lit: *uono* is the talk of the town). This was a common saying in the study site localities and was used to signify the importance of this small pelagic fish species and its association to community livelihoods and the local economy. *Uono* (Eng: Commerson's anchovy, species: *Stolephorus commersonii*) was used as a generic term to refer to all small pelagics of the family Engraulidae found in the area. According to Breuil and Bodiguel (2015), the

**Table 2.** Average range in landings per fishing trip of the most common fish species (NE monsoon, 2017).

| Species (Local name) | English name | Minimum weight (kg) | Maximum weight (kg) |
|---|---|---|---|
| Bangra | Indian mackerel | 1 | 120 |
| Kibua | Indian mackerel | 3 | 700 |
| Dagaa damu | Spotted sardinella | 1 | 50 |
| Uono/Dagaa mchele | Commerson's anchovy | 14 | 2500 |
| Gololi | Big eye scad | 1 | 30 |
| Msumari | Shortfin scad | 12 | 100 |
| Dagaa simu | Indian scad | 15 | 100 |
| Bilibili | n.k | 4 | 35 |
| Dagaa upapa | Rainbow sardine | 5 | 50 |
| Ngarengare | Banded needle fish | 30 | 300 |

Source: Fishers, Field data- PEACC study 2018.

family consists of eight other species, namely *Engraulis japonocus, Stolephorus heterolobus, S. punctifer, S.indicus, S. devisi, Thryssa baelama, T. setirostris* and *T. vitrirostris*. The importance of *uono* is, however, a recent phenomenon in this area. In this paper, the term *uono* is used to refer to all species of the family Engraulidae found in the fisheries of Tanga.

According to oral histories, *uono* fishing used to be an insignificant component of the local fishery, particularly in the fisheries value chain. The fishers, who basically operate a multi-species fishery system, mentioned that some years back, large pelagic and demersal fish species were preferred because of their higher monetary value and abundance. They also recalled that about 70% of the local small pelagic landings were purchased by Interchick Company, a chicken production and marketing company based in Dar es Salaam, which was then the major buyer of dry sardines and anchovies for production of chicken feed in the country. The prominence of *uono* was a phenomenon of the past 10 years. In 2007, it was said, only two villages, Mwaboza and Jasini, were known for *uono* fishing along the Mkinga coastal area. Five years later, by 2012, two other villages, namely Zingibari and Monga-Vyeru, were engaged in *uono* fishing and experienced high catches. By 2017, almost every landing site in Tanga was engaged in the *uono* fisheries and associated business.

*Main species caught and average landings*

The five small pelagic fish species caught most commonly along the coast of Tanga that were mentioned were Indian mackerel, *bangra* (30%), banded needle fish, *ngarengare* (23%), Commerson's anchovy, *uono or dagaa mchele* (34%), and *ziha* (13%). In terms of fish landings, most fishers mentioned that *uono/dagaa mchele* was the most prevalent, followed by other species with varying catches including *bangra, kibua* and *dagaa damu* (Table 2).

As illustrated above in Table 2 above, *uono* was caught in higher quantities than other species.

*Main fishing gear:*

By 2017, the main fishing gear was the ring net. This net, as noted by fishers, represented a complete change in fishing gear over the last 5 years (Fig. 2). The prominence in ring-net fishing within the Tanga fisheries was also noted by Anderson and Samoilys (2016), indicating an increase in the number of ring-nets over time from 46 to 180 in Mkinga District and from 36 to 50 in Tanga District between 2007 and 2013.

The main fishing craft used in the *uono* fishery was the *mashua* (large boat, about 12m long) or *ngwanda* (small boat, about 8m). On average, 87% of the fishers mentioned that they use the *mashua* which had a crew carrying capacity ranging from 15 to 45 persons per fishing trip. The *mashua* is normally accompanied by a number of smaller support crafts (locally called *dau* or *plaud*) on fishing trips, which carry lanterns or hurricane lamps required for illumination to attract the fish, and which surround fishing locations where the nets are cast. *Ngwanda* are also often used to carry the load of fish. The use of other smaller craft for fishing such as *mtumbwi* was found to be minimal, and are mainly used

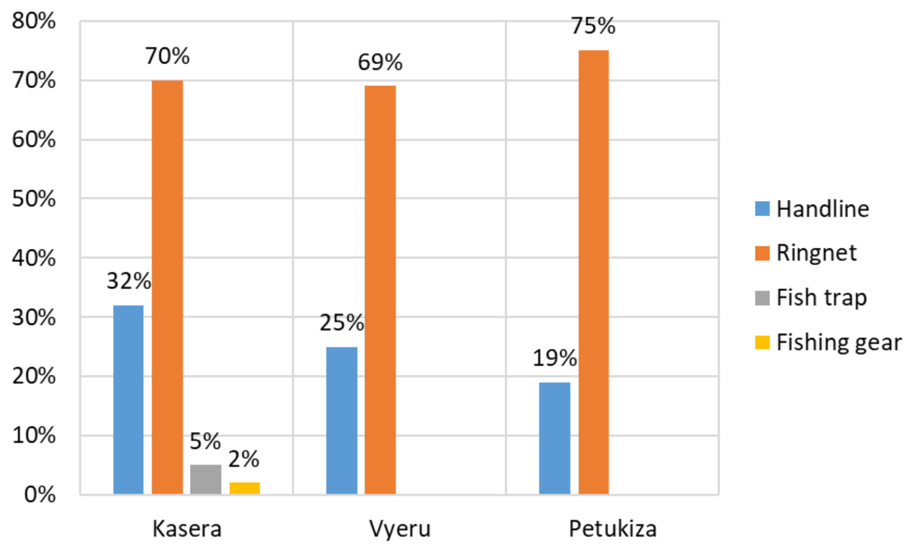


**Figure 2.** Main fishing gear by area used in small pelagic fisheries in Tanga region, north eastern Tanzania (June 2017).

by stake and trap fishers targeting reef fishes. These vessels usually engaged two or three fishers per trip, and were not ideal for *uono* fishing because of their inability for large haulage. Larger fishing crafts were most preferred, but were unaffordable for many fishers.

### *Perceptions on quality of fishing grounds*

Fishers maintained a more or less steady relationship to common fishing grounds. They claimed that there have not been any significant changes in the preferred fishing grounds over the last 5 to 10 years. The seasonally determined patterns of fishing at certain locations in particular weather were largely similar to what had been practiced for the last 10 years. This meant that since the 1990s, fishers have been using the same fishing grounds. Frequently visited fishing grounds in the last 5 years have been around the reefs of Chundo, Wamba, Nyuli, and Jambe (see Fig. 1). Other grounds used less frequently were Mwamba nyama and Boma reefs. Seasonal migration to distant fishing grounds during certain periods was also common, as fishers synchronise their activities with fishing seasons.

Fishers from Vyeru and Petukiza mostly exploited Chundo and Wamba reefs. Vyeru fishers, who are located geographically closer to the reefs, also preferred these fishing grounds because of proximity. Kasera fishers were able to exploit a wider range of fishing grounds (Table 3). The farthest distance that fishers travelled to fishing grounds was 6 km, while the closest was 0.5 km.

## Trends in small pelagic fish catches

Fishers in this study explained that they had been increasingly experiencing changes in the availability of small pelagic fish in the recent past (Fig. 3). About

**Table 3.** Distance covered by fishers to fishing grounds per landing site.

| Distance in Kilometers | Landing sites | | |
|---|---|---|---|
| | Kasera | Vyeru | Petukiza |
| 0.5 | | 6% | |
| 1 | 2% | | |
| 2 | 17% | 13% | 20% |
| 2.5 | 6% | | |
| 3 | 32% | 50% | 53% |
| 4 | 32% | 25% | 20% |
| 5 | 7% | 6% | 7% |
| 6 | 6% | | |
| Total | 100.00% | 100.00% | 100.00% |

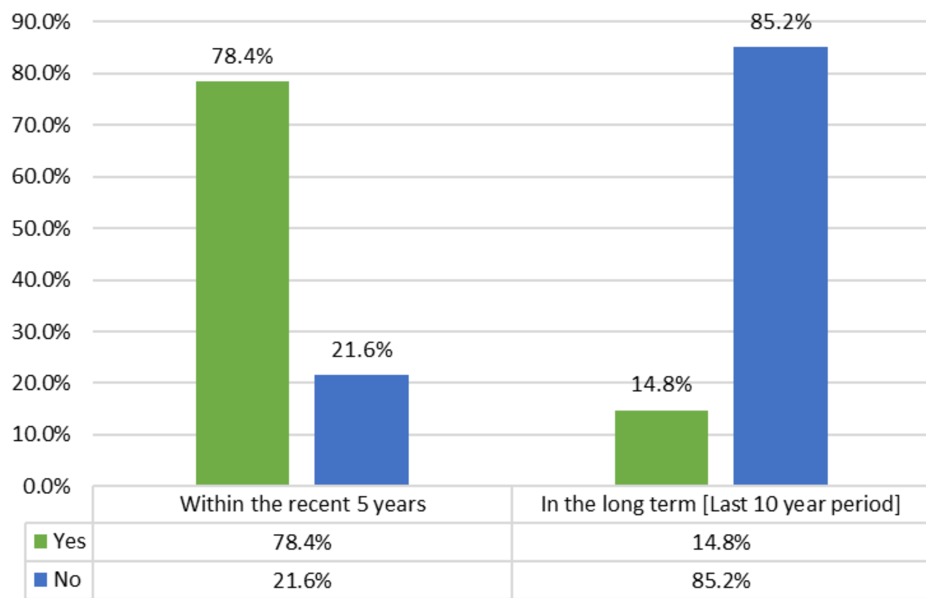


**Figure 3.** Fishers experience of changes in small pelagic fish catches over the long and short term in Tanga (May 2017).

78% of the fishers noted that they had witnessed significant changes in fish catches in the last 5 years (i.e. since 2012) compared to only 15% who had experienced changes in the last 10 years.

Of those who indicated that they have experienced changes in the last 5 years, 32% of the respondents mentioned that there was a sharp decline in fish catches, while 39% indicated that there was a slight decline, and 18% maintained that they had not seen any changes in catches. About 8% of these respondents mentioned that they were catching new species of fish in the last five years, that was explained as obtaining small catches of different species at different times. Obtaining the same species of fish in one major haul was not as common as it used to be in the past.

## Perceived factors causing changes in availability of small pelagic fish

Among the key factors perceived to be responsible for variable fish catches included (i) fishing practices and (ii) weather related factors.

### *Past fishing practices*

Changes to the small pelagic fishery in Tanga was perceived as being directly related to past and present fishing practices, including destructive fishing. These practices were (i) the use of destructive fishing methods that led to a decline in reef and demersal fisheries, (ii) introduction of small-scale purse seines (ring nets), and (iii) expansion of the *uono* market due to increased demand. Firstly, fishers perceived that the *uono* fishery was the inevitable response to the destruction of the neighbouring coral reef ecosystem around Tanga through the use of dynamite. In 2008, Samoilys and Kanyange (2008) note that dynamite fishing in the area had resulted into significant loss of biodiversity and fisheries productivity. The high catches realized with the use of dynamite proved a deterrent to any effort to curb this practice. During this study, it was however claimed that dynamite fishing was no longer a major threat to these fisheries. The beach seine was also used in the past, viewed as a necessary alternative to the less effective traditional fishing methods (gillnets, fish traps and handlines), which had a low productivity potential (Samoilys and Kanyange, 2008).

As a measure to curb dynamite fishing and other forms of destructive fishing methods, the Marine and Coastal Environment Management Programme (MACEMP) working with the coastal area management initiative, Tanga Coastal Zone Management Programme (TCZMP), introduced ring nets as an alternative fishing gear. This initiative significantly changed fishing practices in the area in several ways. Firstly, these nets are species-selective and were ideal for small pelagics, hence fishers began to concentrate more on catching small pelagics (KII, Mkinga DFsO 28/6/2017). The Fisheries Development Division reported that estimated landings of small pelagic fishes in Tanga region increased from under 500 tonnes in 1988 to more than 2,000 by the year 2010 after the introduction of ring nets (Anderson and Samoilys, 2016).

Secondly, this fishing practice demanded a significant amount of labour for managing and hauling the catch, and engaged more people as boat crew, albeit varying in numbers according to seasons. Thirdly, according to the fishers, the use of ring nets not only enabled them to catch small pelagics in plenty, but they also reduced the use of dynamite, since, as one fisher explained, '*uono haupigwi bomu, unautegea kwa taa, kama mchumba unamlewesha na mwanga- vitu vya kung'aa, nae anakuja tu'* (lit: *uono* is not caught by dynamite, you trap it with lanterns, it is coaxed as one woos a lady with shiny things, and she just comes willingly). This saying implied that destructive methods were not ideal for *uono* fishing, hence have allowed for fish populations to multiply.

At the same time, the market for *uono* expanded beyond Tanga and Dar es Salaam, as a result of inadequate supply of the much preferred *dagaa* from Lake Victoria to satisfy the increasing local and international markets (FGD with Skippers, Sahare landing site, 27 June 2017). Traders come from as far as Arusha and the Democratic Republic of Congo (DRC). This growing market spurred local production of *uono*, and indeed, the local economy. Experiences of the more recent past (from 2012) was however attributed to many other factors that caused negative impact on the fisheries as shown in Fig. 4.

### *Recent fishing behaviour*

In all communities, it was claimed that the population of fishers was increasing significantly. This increase may have partly been influenced by changes in fishing methods that allowed the entry of more fishers. Although exact data on the number of fishers could not be established during this study because of lack of records, it was claimed that the open access nature of Tanzanian coastal fisheries permitted an unregulated influx of fishers to the local fishing grounds. The number of registered vessels per landing site was often topped up by seasonal migrant fishers who visited the fishing villages during peak fishing seasons. Some migrant fishers would set up temporary camps (*dago*) and their numbers were noted. But it was reported that many more would visit local fishing areas without officially declaring their entry to local authorities along the Tanga coast.

A related concern was daylight fishing with ring nets, which was said to be not only coercive, but was also claimed to be contrary to customary fishing norms. A local fisher explained, *fishing uono during the day demanded 'seeking and chasing it wherever it has settled, and catching juveniles without restraint, and hence destructive*" (MA, Sahare, 27/09/2017). The timing of fishing was thus a controversial issue especially between local fishers and the more resourced migrant fishers. Local fishers claimed that traditional fishing patterns for *uono* (which specified periods for daylight fishing to be conducted only during the months of June,July and August), and also respect of breeding seasons were

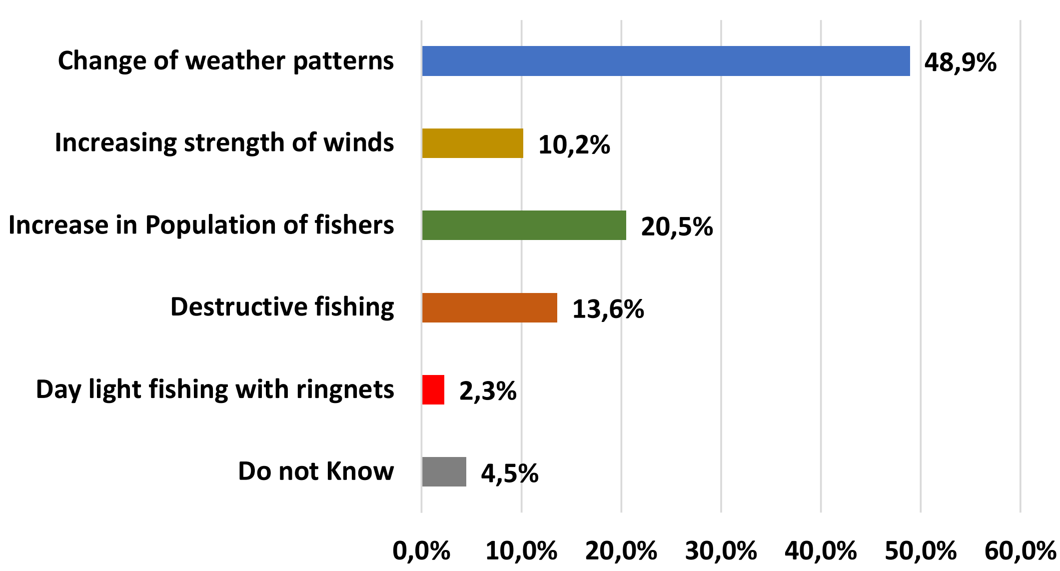


Figure 4. Perceptions on factors contributing to changes in small pelagic catches in Tanga region, Tanzania (May 2017).

being violated. Kasera landing site noted 10 fishing crafts which caught fish in daylight along the Sahare coast in inshore waters, and 20 others fishing further offshore (KII, Kasera Landing Site, Fisheries Officer). About 70 vessels were engaged in night-time fishing. Another fisher at Sahare complained, "*mavuvi ya uono sasa yamekuwa hayana matulizo, uko kila siku, si kusi wala kaskazi, una lazimishwa na wavuvi wa mchana*" (lit: *uono* fishing has now become a daily affair, and there is no resting nowadays, neither during the southerlies, nor during the northerlies, it is constantly forced by daylight fishers (AK, Sahare, 26/09/2017). The decline in *uono* fisheries in the recent past was thus attributed to lack of effective traditional restrictions.

### Perceptions of upwelling and availability of small pelagic fish

The NE monsoon period was mentioned as particularly productive because of the availability of nutrients on the surface (Fig. 5).

However, despite recognising a relationship between upwelling conditions and the availability of small pelagic fish, fishers could not directly attest to these conditions as the primary source of productivity in the fisheries. Levels of productivity of the fisheries were understood as normal responses to the seasonal and weather changes. A total of 61.3% of the fishers indicated that they did not know that the phenomenon had any significance to the fisheries, while only 27% indicated that it had an impact on the fisheries. About 50% indicated that the normal seasonal weather changes generated the desired functioning of the small pelagic fisheries, bringing about their abundance at certain times, but also a period where the fisheries were supposed to be left idle to allow rejuvenation. The inter-monsoonal seasons (locally known as *leleji/maleleji*) were mentioned to be the best fishing periods because of the calm weather conditions, and also the times that small pelagics become plenty. Of the two interchanging monsoons, that from the NE to SE resulted in more abundance of small pelagics than that from the SE to NE.

### Conditions on the fishing grounds:

The perception of fishers of the significance of upwelling was also examined in relation to how they gauged the best fishing grounds. Fishers in all three landing sites mentioned that they have not changed fishing grounds for a long time. This was because these fishing grounds were still seen as reliable locations with respect to small pelagic fishes, and also, because of their continued ability to access these grounds irrespective of weather changes. Some of the reefs were favoured by the fishers because they were sheltered during bad weather. Knowledge of breeding patterns was another indicator that established how fishers related to the availability of small pelagics. About 59% mentioned that small pelagics breed around reefs and the pebbles around these reefs (kis: *kwenye miamba na changarawe),* and 22% stated that they breed along water currents (kis: *mkondo wa bahari*). In terms of breeding season, 45% of the fishers claimed that the best breeding season was during the NE monsoon, compared to

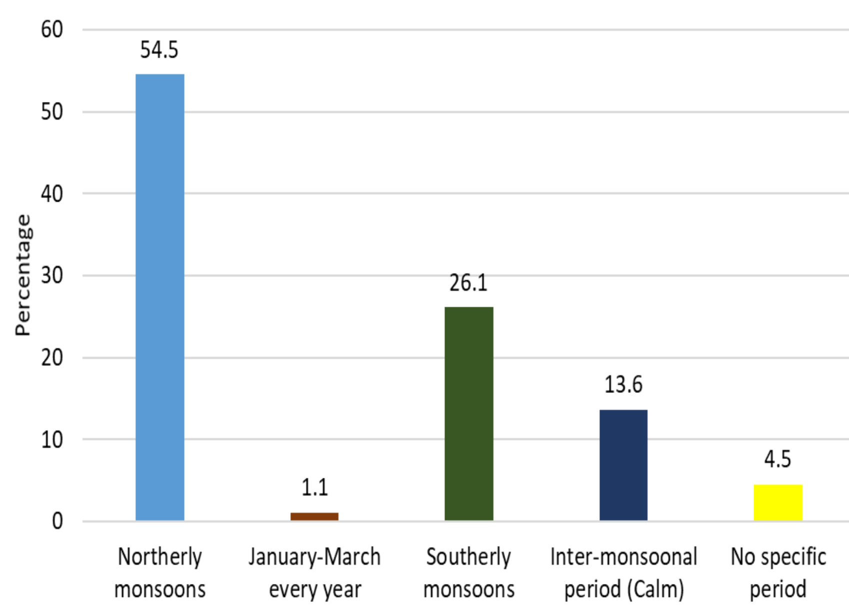


**Figure 5.** Distribution of small pelagic catches by seasons based on respondents.

28% who mentioned the SE monsoon. About 18% mentioned the inter-monsoonal period (kis: *maleleji)*, and the rest did not know.

In addition, fishers maintained that small pelagics concentrate in the vicinity of the reefs and along water currents (*kwenye mikondo*) where it is believed that "*mchanganyiko wa maji unaleta samaki wengi zaidi"* (lit: mixing of water brings many fish). Mahongo and Shaghude (2014) mention that water currents along these reefs form part of the East African Coastal Current (EACC) system whose main core passes offshore on the eastern side of the Islands of Pemba and Zanzibar, but a smaller branch enters the Pemba Channel through the entrance separating the islands of Zanzibar and Pemba. The authors also noted that the EACC was relatively weak, but flows northwards throughout the year. Fishers were able to determine the location of these currents by their relatively higher water speeds compared to surrounding areas. During the NE monsoon, there is enhanced mixing with bottom water coming to the surface, leading to the surface water becoming "dusty" after scouring debris, sand, broken corals, seagrass and other bottom materials. According to the fishers, the NE monsoon "cleans" the ocean at the end of the season.

About 72% of the fishers however mentioned that over the recent past, there have been changes in the locations of water mixing '*mchanganyiko wa maji*' (lit: mixing of waters), while 17% denied any such experience, and 11% did not know. Elaborating, 15% of them associated these changes with an increase in the strength of currents (kis: *kasi ya maji*), and the rest mentioned that there is a shift in their location. However, only 32% of the fishers target these new locations for fishing, and the rest have not changed their regular fishing grounds on the understanding that these new locations were not necessarily significant to fishing success.

## Small-pelagic fisheries and local livelihoods

Changes in the availability of small pelagic fish had a significant impact on the welfare of fisheries- dependent communities in terms of (i) access to incomes and employment for women in an expanded value chain, (ii) simpler processing and handling of fish, and (iii) household protein consumption. These aspects were experienced differently with changing availability of small pelagic fishes. It was found that the value chain of the small pelagic fishery engaged many more actors than what had been experienced in the fishing of larger fish species. Women in particular mentioned how the small pelagic fisheries allowed them to work in off-loading the catch as porters locally known as *Wabebaji*, in addition to the activities of gleaning, catching of small shrimp, fish processing and fish mongering. *Ubebaji*, which is currently a significant part of the small pelagic fisheries value chain in Tanga, has widened opportunities for income generation for many women after experiencing a decline in other sources of livelihood, including inland agriculture and was are perceived as petty trades.

The marketing of *uono* was also simpler. The fish was sold to traders at landing sites, usually directly from the vessels after they docked. This system was different from how fish were marketed in other landing sites in Tanzania where the fish was auctioned at defined market places. In the case of *uono*, a small portion of fresh *uono* was usually sold to local consumers while the bulk was immediately processed through braising and drying for transporting to distant markets. Women respondents explained that this processing was relatively easier to handle than with larger reef fishes. One of them said, "you need a fridge or other means of preservation for large fish after harvesting, while *uono* simply needs braising and drying" (Fisher, Sahare, 4/7/2017). It was also established that post-harvest loss was minimal for small pelagics because of immediate processing.

Another important livelihood impact related to the small pelagic fisheries was the level of intake in household protein consumption. Although actual measurements of protein intake by households could not be established in this study, it was generally accepted that small pelagics, dry or fresh, were part of the diet in fishers' and porters' households almost daily, and was a common dish at the local restaurants (*migahawa*). Less advantaged households were those without members who provided active labour in the value chain, who had to buy or request for a handful of fish, hence the saying, "*increasingly in bad times, even a bowl of uono for relish cannot be offered to you*"!

Declining catches over the last few years have thus had various impacts in the communities. The biggest impact was in terms of declining incomes for individuals and for the general community, specifically experienced during the last 5 years (Table 4).

Declining catches also affected the level of transactions between sellers (fishers) and buyers (small and

**Table 4.** Felt impacts from sampled fishers in Tanga region of changes in catches over the short term (5 years, 2012-2017) by level and severity.

| | Individual level impacts | Percentage | Community level impacts | Percentage |
|---|---|---|---|---|
| 1 | Significant drop in income levels | 34% | Buyers affected by not getting fish | 43% |
| 2 | Significant drop in fish catches | 31% | Significant drop in community incomes | 23% |
| 3 | Shaken individual welfare | 10% | Inability to cater for household needs | 10.5% |
| 4 | Rise in income (fish prices have gone up) | 6% | More profits in fish trade (price of fish has gone up) | 10.5% |
| 5 | Health issues due to extreme cold while at sea | 3% | Increased mobility in seeking income | 9% |
| 6 | Inability to cater for family needs | 3% | Social unrest (theft of livestock) because of poor paying fisheries | 3% |
| 7 | Decreased access to social services (lack of reliable income) | 3% | Do not know | 1% |
| 8 | Wait for conducive weather | 10% | | |
| | Total | 100 | | 100 |

big traders), and had also negatively affected the relationships between the range of other actors in the small pelagic value chain such as fish porters (*wabebaji*) and processors. At the same time, declining catches meant higher prices of fish for traders and fish mongers. But fish porters were getting less fish to upload, leading to frequent scrambling between men and women. BMU officials in Vyeru explained that in order to reduce the unregulated scrambling for offloading fish, they introduced a registration system for the porters who were given a number recorded on the container used for offloading. In June 2017, there were more than 200 registered containers at Vyeru landing site. Porters were also required to queue as the fishing craft landed and approach them in that order, but decreasing catches disrupted this organized system. This system was also intended to allow fishers or traders to track porters after offloading to minimize incidences of loss.

Other indirect impacts mentioned included increasing theft of small items in people's neighbourhoods. Theft of chickens was said to be on the increase because of what an elderly respondent said "young men do not earn enough from the fisheries nowadays. Hence, they steal small things to sell elsewhere for a living" (MK, Vyeru, 24/11/2017). Fishers were perceived to be the hardest hit by declining catches (mentioned by 43% of respondents - youth of under 18 years (16%), households/families (14%), women (6%), and men in general (mentioned by 4%).

## Livelihood vulnerability from changing fisheries

Generally, fishers and the community members expressed their fear of livelihood decline which was aggravated by their inadequacy to cope with changing fisheries. Among the factors noted to influence people's vulnerability included: (i) Perceptions and understanding of risk factors, (ii) Over-reliance on a single livelihood source - the fishery, and (iii) Nature of external support systems.

### Perceptions of risk factors

The biggest perceived risk was related to human-induced factors, such as increasing population of fishers, fishing intensification and especially, unregulated patterns of fishing. Although fishers acknowledged that changes in weather patterns have been more frequent and severe over the last 5 years (2012-2017), changes in such natural processes were generally not viewed as significant risk factors to their livelihoods.

Of importance was how the fishers' viewed their own inability to access distant fishing sites due to poor technologies, and how this was perceived as a major hindrance in allowing them to cope with the implications of changes in sea water conditions. Although the study noted that a few skippers used GPS, which has improved access to desired fishing grounds because of maximized accuracy in targeting distant fishing grounds, they were few, not local, and mostly from Zanzibar. In addition, although changes in the timing of best fishing periods were sometimes still associated with the changing patterns in weather conditions, fishers perceived the latter as natural events and inevitable changes within the sea.

A bigger concern of fishers with regard to unexpected bad weather such as strong winds, heavy rains and unexpected storms, was for their own safety. Poor technologies affected their capacities to prevent and cope with disasters at sea. Most of them did not carry enough safety equipment to cater for the entire fishing crew. In one FGD at Sahare, community members stressed that they needed fibre-glass boats (locally named as '*faiba*') in the belief that these are fast and efficient and able to save fishers during weather disasters (FGD with Skippers, Sahare, 27/6/2017). Vessel wreckage during storms was said to happen now and then, and fishers only had other fishers to save them during such incidents. Hence their insistence on fishing around reefs that were 'sheltered'.

### Overreliance on a single livelihood source

The overriding dependence on the small pelagic fishery by local communities limited their ability to cope with changing sea conditions in the recent past. The small pelagic fisheries generated a web of inter-dependence and inter-relationships connecting individual fishers, women, families, traders and other community members. The vibrancy of these relationships could be witnessed during bumper catches. The decline in fish catches however, exposed the weaknesses in these relationships. Many members relied on small pelagic fisheries as the single and most important livelihood source. Very few fishers had another viable source of livelihood (Table 7). Women porters expressed that fish offloading (*ubebaji*) gave them access to a more reliable and immediate source of income than toiling as a worker in some of the eating places (*mgahawa/hoteli*) or, in farming. The average income as a *mgahawa* worker was about Tshs 2000 (approx. USD 0.8) a day, while a porter could earn up to Tshs 10,000.00 (approx. USD 4.9) a day from the work. *Ubebaji* also gave them more dignity as independent income earners.

### Information on changing fisheries

Inadequate capacity in making predictions about the weather, and in identifying locations with the best fisheries in the context of climate-related upwelling conditions, was a major factor that added to the vulnerabilities of these communities. In all three sites it was observed that fishers and fishing communities did not have access to reliable and timely information about weather conditions that influenced changes in the fisheries. Fishers therefore could not effectively take advantage of upwelling locations to maximize their fishing catches.

In this regard, several key institutions had the responsibility to promote the productive use of the fisheries by communities, including enhancing their adaptive capacities to changes. These institutions included national and local government fisheries offices, national weather and transport agencies, grassroots level governance structures such as village governments and the Beach Management Units (BMUs) of Petukiza and Vyeru landing sites, and the sub-hamlet government and Coastal Conservation Committee at Kasera landing site. The study also examined how and from what sources fishers receive weather-related information (Table 5).

It was found that fisheries officials in both Tanga Municipality and Mkinga District did not have a systematic programme for formal communication to small-scale fishers about weather changes (KII, TA, 29/11/2017). In addition, the Tanzania Meteorological Agency (TMA)

**Table 5.** Fishers' sources of information on weather conditions affecting the sea (November, 2017).

| Source | Frequency | Percent |
|---|---|---|
| Never been informed | 34 | 38.6 |
| Through the media (radio) | 52 | 59.1 |
| Learn through own experience | 2 | 2.3 |
| Total | 88 | 100 |

Source: Field data: PEACC Socioeconomics study, May 2017 which is mandated to provide weather forecasts and national climate outlooks was not directly connected to Tanga coastal fisheries. The closest interaction with communities related to information on weather related aspects came from occasional visits conducted by the National Surface and Marine Transport Authority (SUMATRA) to provide education on safety at sea for fishing crews. Fishers at Kasera landing site (Sahare) mentioned that SUMATRA officials had once visited them (in 2016) and distributed some life jackets as part of their awareness raising programmes. They had not paid another visit to the landing site since then. The radio was mentioned as the most resourceful media for weather forecasts, but was unfortunately not always used for fishing trips.

According to the fishers, their association with fisheries officials was occurred in three major ways: *Kukagua* (Inspection); *Kukata leseni* (Licensing); and *Kulipa ushuru* (Paying taxes). The fishers thus felt that they were left to encounter changing conditions of the sea on their own, and were usually not informed or enlightened about strategies to identify more lucrative fishing locations. Hence, they kept on relying on traditional means of weather prediction, '*reading the seas'*. Fishers also complained that they were not adequately supported with efficient fishing vessels to be able to access distant productive areas offshore. Even though they sometimes detected certain locations as possibly lucrative for fishing ground, they failed to take full advantage of these locations because of poor vessels which could not venture offshore.

## Adaptive capacity to changing fisheries

Given their experiences of vulnerability, different community groups in the study area responded differently to changing conditions in the local fisheries, drawing on different assets at their disposal. Despite declining catches, most fishers were hesitant to leave the fisheries and opt for other livelihood activities. Most of the responses indicated an inclination to periodic and 'circular' shifts either in fishing grounds or fishing times, but within the same small pelagic fishery. The responses did not give any indication of a planned reaction to any changes in the fisheries, but rather a more generalized reaction to conditions as they were experienced. The most viable response option mentioned was the need to acquire better seaworthy equipment such as modern fishing vessels (Table 6).

As illustrated above, about 45% of the fishers assumed a resigned attitude to change, while others assumed that more efficient technology would be a better solution. Shifting to other fishing grounds in accordance with changing seasons was also mentioned as a viable option that would allow them to remain in the fisheries.

At the household level there was a combination of intra-household and inter-household adaptation strategies. Women for example, explained that they capitalized on local support systems such as social networks, which included seeking loans from neighbours/relatives, and occasionally asking for relish from a neighbour or fishers for the daily meal; a common practice seen in coastal communities of Tanzania. A less preferred option was to reduce household consumption costs through purchasing cheaper food items or clothing. Other common coping strategies mentioned included putting aside savings (in anticipation of harder times ahead), but since savings

**Table 6.** Perceptions of fishers and expressed adaptation options to changing fisheries.

| Type of response | Percentage |
|---|---|
| No viable option | 45 |
| Seeking seaworthy equipment – modern vessels | 30 |
| Seeking business opportunities, credit | 9 |
| Shifting from depleted grounds to other fishing sites | 7 |
| Consulting and learning from fishers' knowledge on weather | 3 |
| Reducing tax rates | 2 |
| Keeping savings to cater for bad fishing times | 2 |
| Migrating | 1 |
| Total | 100 |

depended on the vibrancy of the small pelagic fisheries, this was hardly affordable for poor households. Other households sought alternative income generation activities such as daily paid labour. Investing in other activities such as small businesses was however also difficult because of inadequate capital. Many women voiced this constraint in the FGDs.

The general pessimistic attitude towards viable options was observed to be influenced by people's desire to maintain their engagement with the fisheries. Men were more at risk in accessing viable response options than women in this regard because of the nature of activities in fishing communities. Options such as modern beekeeping or fish farming (currently developed in other coastal communities in Tanga region) were seen as not viable because of their operational requirements and experiences of poor past performance. Similarly, Anderson and Samoilys (2016) note the significant challenges that coastal communities have encountered in promoting alternative livelihood activities with reasons ranging from scale of operations, to viability and sustainability. In view of the generalized vulnerabilities that these communities experienced, the most reliable modes of adaptation were collaborative efforts, but within the same fishing areas (Table 7).

## Conclusions

This study examined the experiences and responses of fishers and fishing communities to variability and changes in climate and climate-related phenomena such as upwelling, and the consequent changes in the productivity of small pelagic fisheries. What is evident is that there are different ways through which fishers communicate about changes in the fisheries, or changes in the conditions of the sea, depending on how it affects their livelihoods. Their increasing experience of fewer catches during the NE monsoon period, which is also believed to be the period of high productivity, raises questions related to fishing capabilities during periods of enhanced wave action and turbulence, suggesting more research is necessary to compare productivity levels between this season and the calm (interchanging) monsoon seasons, which fishers claim to obtain better catches. It is also important to examine whether there is a lag between nutrient enrichment associated with upwelling and enhanced small pelagic fisheries productivity, which occurs during these interchanging monsoon periods, as experienced by fishers.

The study has also shown that, although fishers do not directly understand the relevance of upwelling-related conditions to productivity in the fisheries, their experience of enhanced fisheries productivity is sometimes associated with those areas and periods when upwelling conditions are said to occur. However, given the nature of changing sea conditions due to current influences of climate change, conditions related to upwelling may not be readily comprehensible to fishers whose major knowledge base has been related to natural seasonal weather patterns. Their vulnerability to livelihood decline is possibly due to their inability

Table 7: Modalities of adaptation measures.

| | Response option | Level | Gender | Mode |
|---|---|---|---|---|
| 1 | Seeking alternative fishing grounds | Individual/Collaborative/Optimistic | Men | Circular |
| 2 | Increasing fishing efforts | Individual/Collaborative/Optimistic | Men | Periodic |
| 3 | Seeking alternative livelihood options. | Individual/Optimistic | Men, Women | Short-term |
| 4 | Compliance to fishing regulations | Authority/Pessimistic | Men | Short-term |
| 5 | Using savings | Individual/Pessimistic | Men, Women | Intermittent |
| 6 | Seeking support through networking, relatives | Individual/Collaborative/Optimistic | Men, Women | Periodic |
| 7 | Not able to do anything different | Individual/Pessimistic | Men | - |

to take advantage of more potential lucrative fishing areas because of limited prediction capacities and the lack of relevant scientific information.

In addition, the multiple and varied ramifications that changes in small pelagic fish catches have had across community groups by occupation and gender in the Tanga fisheries illustrates the importance of understanding the small-scale fisheries as a web of associations, within which multiple level vulnerabilities and adaptation capacities can be realized. Indeed, the varying levels of adaptive capacity of the population groups are influenced not only by their different abilities to draw on different resources, but also by their perceptions and hence responses to risk. New experiences open up varying adaptation options for certain population groups within the same fisheries, with positive or negative implications to livelihoods. Limited options are making people to resort to periodic and often short-term measures informed largely by local knowledge of livelihood patterns. The relevance of sharing and integrating experiences and knowledge in current fisheries management is thus of paramount importance.

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## References

Adewale TA, Fregene BT, Adelekan IO (2017) Vulnerability and adaptation strategies of fishers to climate change: Effects on livelihoods in fishing communities in Lagos State, Nigeria. In: Climate change adaptation in Africa. Springer, Cham. pp 747-757

Adger WN (2006) Vulnerability. Global Environmental Change 16 (3): 268-81

Anderson J, Andrew T (eds) (2016) Case studies on climate change and African coastal fisheries: a vulnerability analysis and recommendations for adaptation options. FAO Fisheries and Aquaculture Circular (C1113): R1

Anderson J, Samoilys M (2016) The small pelagic fisheries in Tanzania, Chapter 2. In: Anderson J, Andrew T (eds) Case studies on climate change and African coastal fisheries: a vulnerability analysis and recommendations for adaptation options. FAO Fisheries and Aquaculture Circular (C1113): R1

Breuil C, Bodiguel C (2015) Report of the meeting on marine small pelagic fishery in the United Republic of Tanzania. SFFAO/2015/34. IOC-SmartFish Programme, FAO. 96 pp

Burton C, Cutter SL (2008) Levee failures and social vulnerability in the Sacramento-San Joaquin Delta area, California. Natural Hazards Review 9 (3): 136-49

Cheung WWL (2015) Impacts of global change on coastal upwelling ecosystems and fisheries. IMBIZO Trieste, Italy, 27 October, 2015

Cinner JE, Daw T. McClanahan TR (2009) Socioeconomic factors that affect artisanal fishers' readiness to exit a declining fishery. Conservation Biology 23 (1): 124-30

Cinner JE, McClanahan TR, Graham NA, Daw TM, Maina J, Stead SM, Wamukota A, Brown K, Bodin Ö (2012) Vulnerability of coastal communities to key impacts of climate change on coral reef fisheries. Global Environmental Change 22 (1): 12-20

Daw T, Adger WN, Brown K, Badjeck MC (2009) Climate change and capture fisheries: potential impacts, adaptation and mitigation. Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530: 107-50

Faleiro F, Pimentel M, Pegado MR, Bispo R, Lopes AR, Diniz MS, Rosa R (2016) Small pelagics in a changing ocean: biological responses of sardine early stages to warming. Conservation Physiology 4 (1): cow017

Forster J, Lake IR, Watkinson AR, Gill JA (2014) Marine dependent livelihoods and resilience to environmental change: a case study of Anguilla. Marine Policy 45: 204-12

Islam MM, Sallu S, Hubacek K, Paavola J (2014) Vulnerability of fishery-based livelihoods to the impacts of climate variability and change: insights from coastal Bangladesh. Regional Environmental Change 14 (1): 281-94

Katikiro RE (2014) Perceptions on the shifting baseline among coastal fishers of Tanga, Northeast Tanzania. Ocean & Coastal Management 91: 23-31

Klutse NAB, Nunoo FKE (2016) The small pelagic fisheries of Ghana. In: Anderson J, Andrew T (eds) Case studies on climate change and African coastal fisheries: a vulnerability analysis and recommendations for adaptation options. FAO Fisheries and Aquaculture Circular (C1113): R1

Koya M, Dash G, Kumari S, Sreenath KR, Dash SS, Ambrose TV, Shyam SS, Kripa V, Zacharia PU (2017) Vulnerability of coastal fisher households to climate change: A case study from Gujarat, India. Turkish Journal of Fisheries and Aquatic Sciences 17: 193-203

Lam VW, Cheung WW, Swartz W, Sumaila UR (2012) Climate change impacts on fisheries in West Africa: implications for economic, food and nutritional security. African Journal of Marine Science 34 (1): 103-17

Mahongo SB, Shaghude YW (2014) Modelling the dynamics of the Tanzanian coastal waters. Journal of Oceanography and Marine Science 5 (1): 1-7

Miller SD (2014) Indicators of social vulnerabity in fishing communities along the West Coast Region of the U.S. MPP Essay. Oregon University, December 1, 2014

Nirmale V, Sontakki BS, Biradar RS, Metar SY, Charatkar SL (2007) Use of indigenous knowledge by coastal fisher folk of Mumbai district in Maharashtra. Indian Journal of Traditional Knowledge 6 (2): 378-82

Oliver-Smith A (2009) Sea level rise and the vulnerability of coastal peoples: responding to the local challenges of global climate change in the 21st century. UNU-EHS

Perry RI, Sumaila UR (2007) Marine ecosystem variability and human community responses: The example of Ghana, West Africa. Marine Policy 31 (2): 125-34

Shirley WL, Boruff BJ, Cutter SL (2012) Social vulnerability to environmental hazards. In: Hazards, vulnerability and environmental Justice, May 4. Routledge. pp 143-160

Shyam SS, Sathianandan TV, Swathi Lekshmi PS, Narayanakumar R, Zacharia PU, Rohit P, Manjusha U, Antony B, Safeena PK, Sridhar N, Rahman MR (2015) Assessment of fishers perception in developing climate change adaptation and mitigation plans. Journal of the Marine Biological Association of India 57 (1): 21-30

Samoilys MA., Kanyange NW (2008) Assessing links between marine resources and coastal peoples' livelihoods: perceptions from Tanga, Tanzania. IUCN Eastern and Southern Africa Regional Office, Nairobi. 27 pp

Tobisson E, Andersson J, Ngazi Z, Rydberg L, Cederlöf U (1998) Tides, monsoons and seabed: local knowledge and practice in Chwaka Bay, Zanzibar. Ambio 27 (8): 677-685

Varela R, Álvarez I, Santos F, Gómez-Gesteira M (2015) Has upwelling strengthened along worldwide coasts over 1982-2010? Scientific reports 5: 10016 [doi: 10.1038/srep10016]

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