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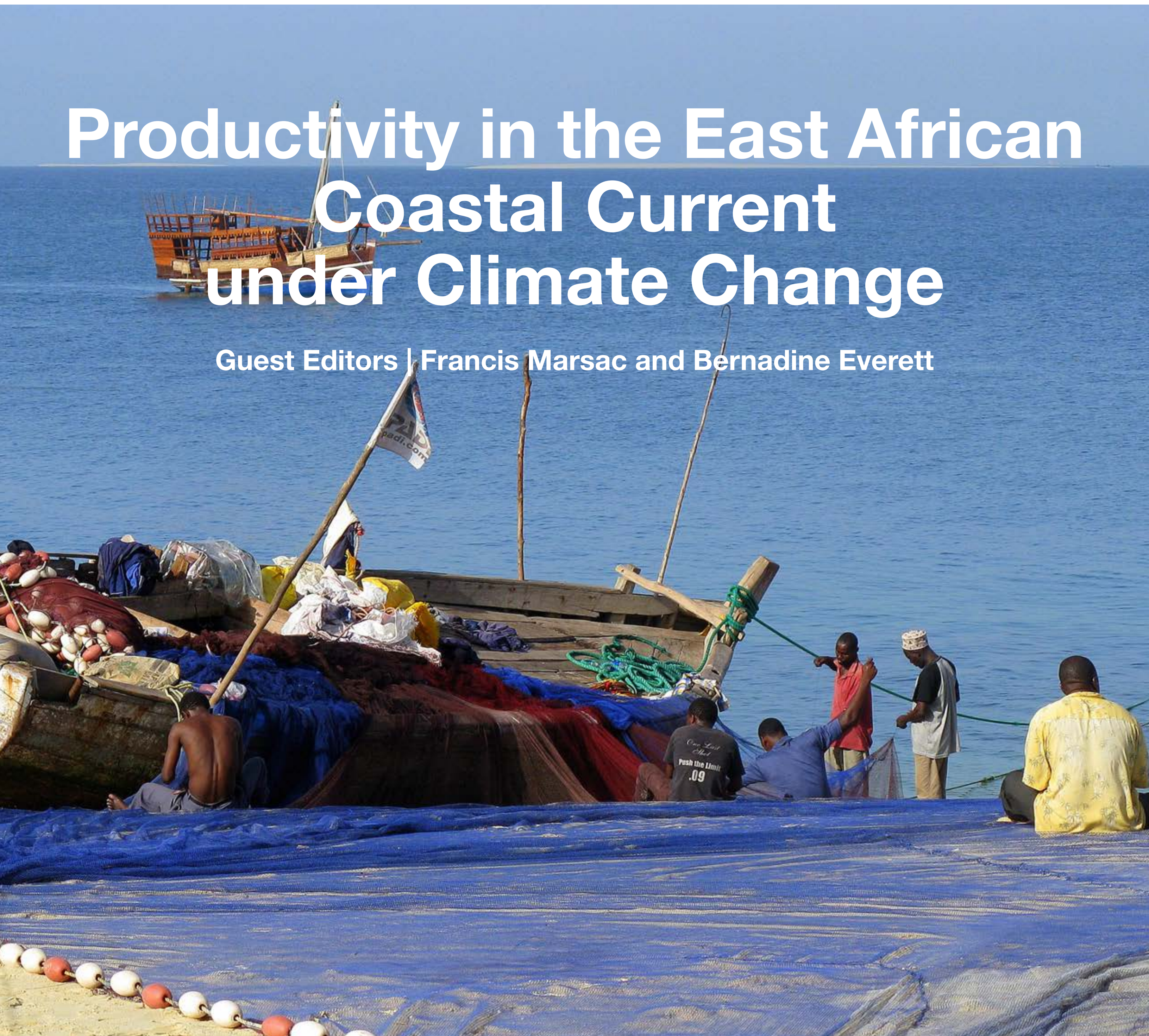

Productivity in the East African Coastal Current under Climate Change

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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).

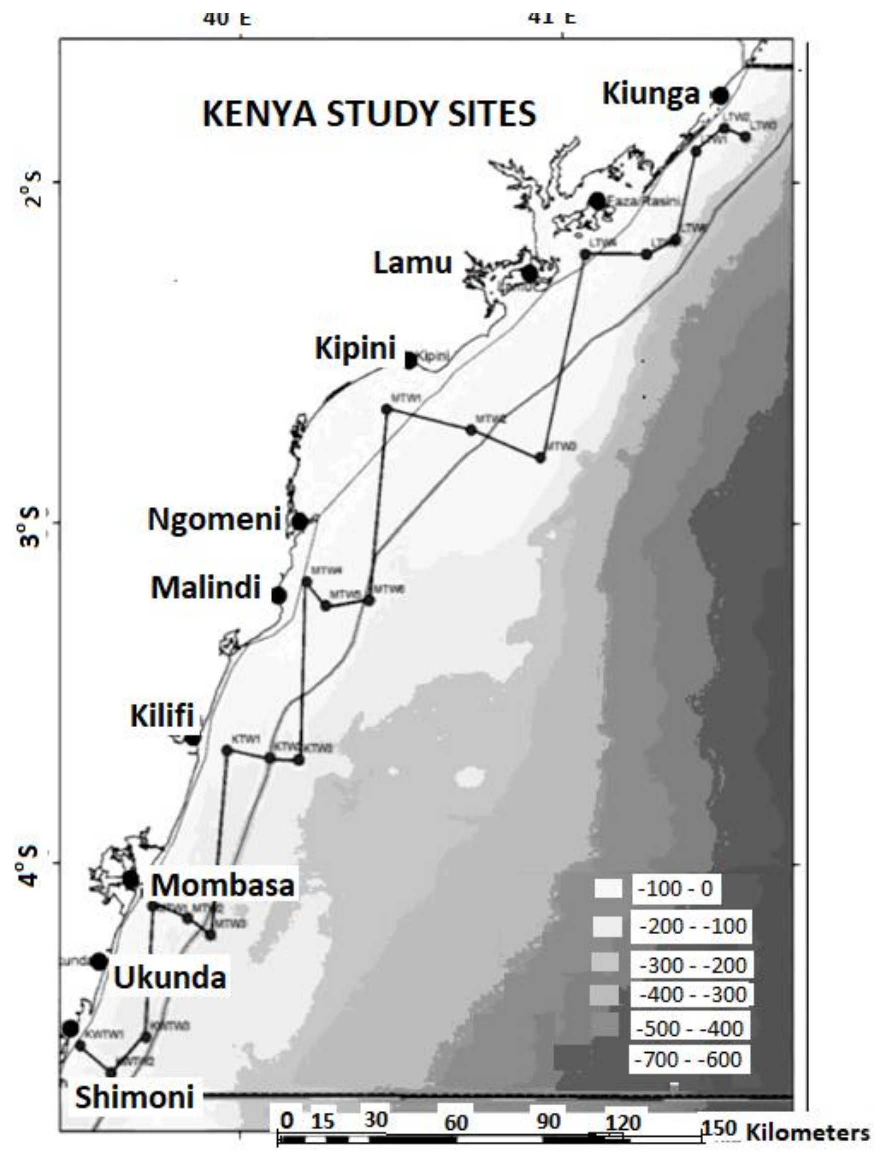

Figure 1. Map showing the location of sampling stations off the coast of Kenya.

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 mid-water maxima might not provide an exhaustive explanation to the high signal in region A. Whereas the

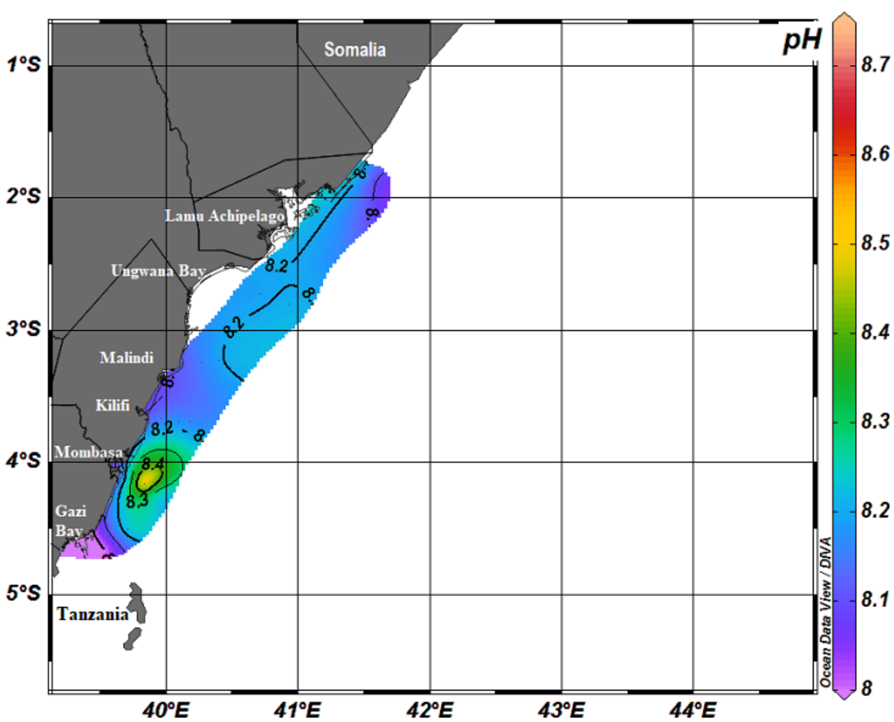

Figure 2. Spatial surface pH distribution within the territorial waters of Kenya.

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.

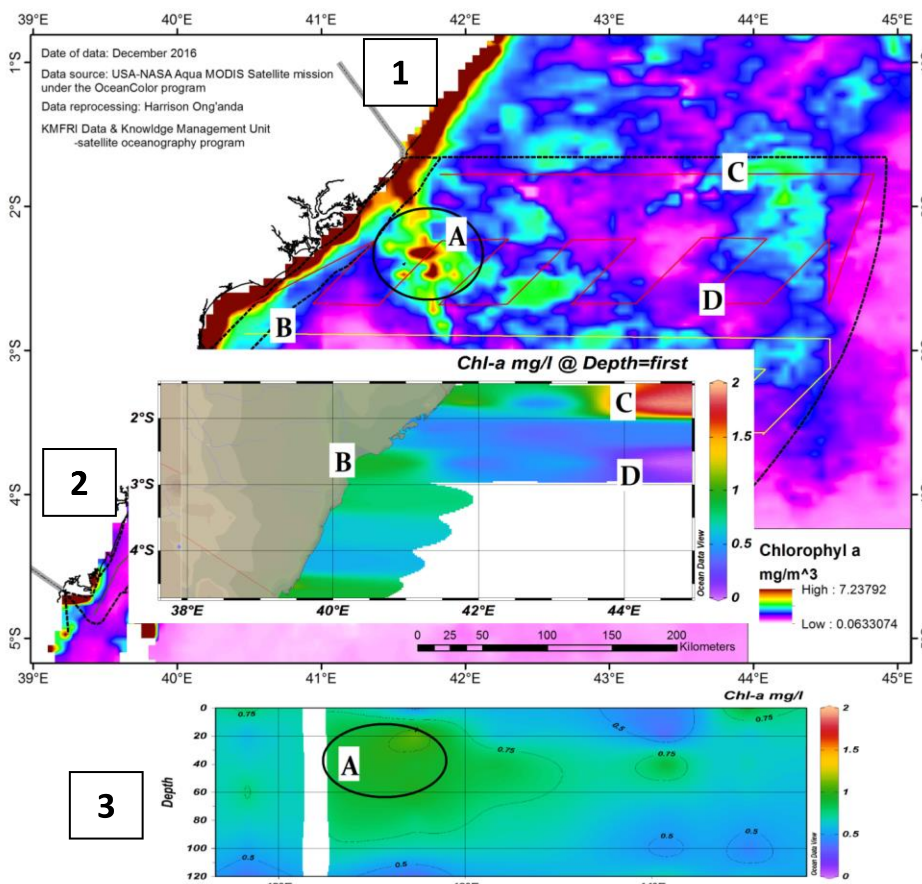

Figure 3. Spatial surface chlorophyll-a distribution as determined during the December 2016 RV *Mtafiti* cruise and as presented by ocean colour Aqua MODIS satellite data. The plot labeled 1 represents the satellite image; plot labeled 2 represents surface spatial chlorophyll-a distribution; plot labeled 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

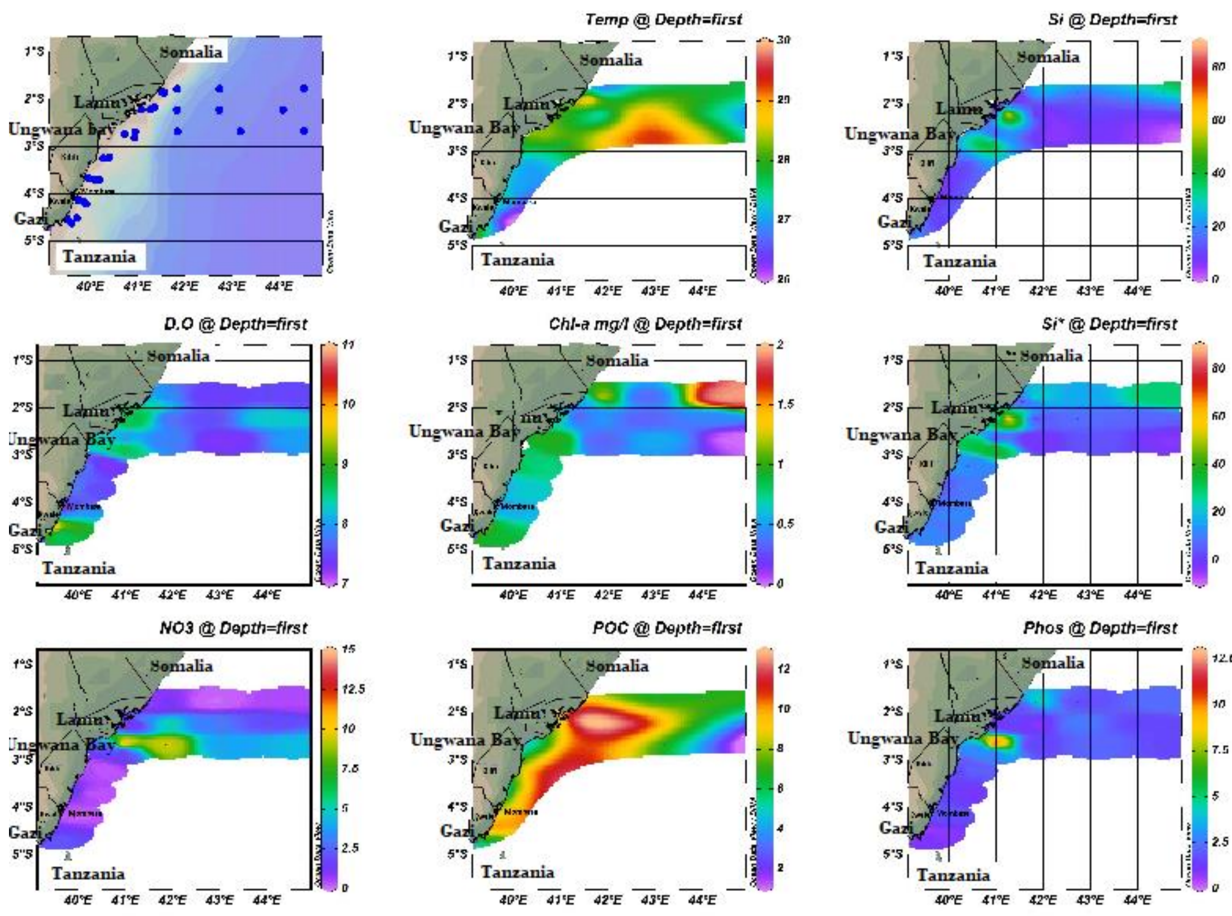

Figure 4. Spatial surface distribution of DO, POC, NO_3^-, Phosphate, Chl-a, Si*,Si and temperature, as determined during the December 2016 RV *Mtafiti* cruise.

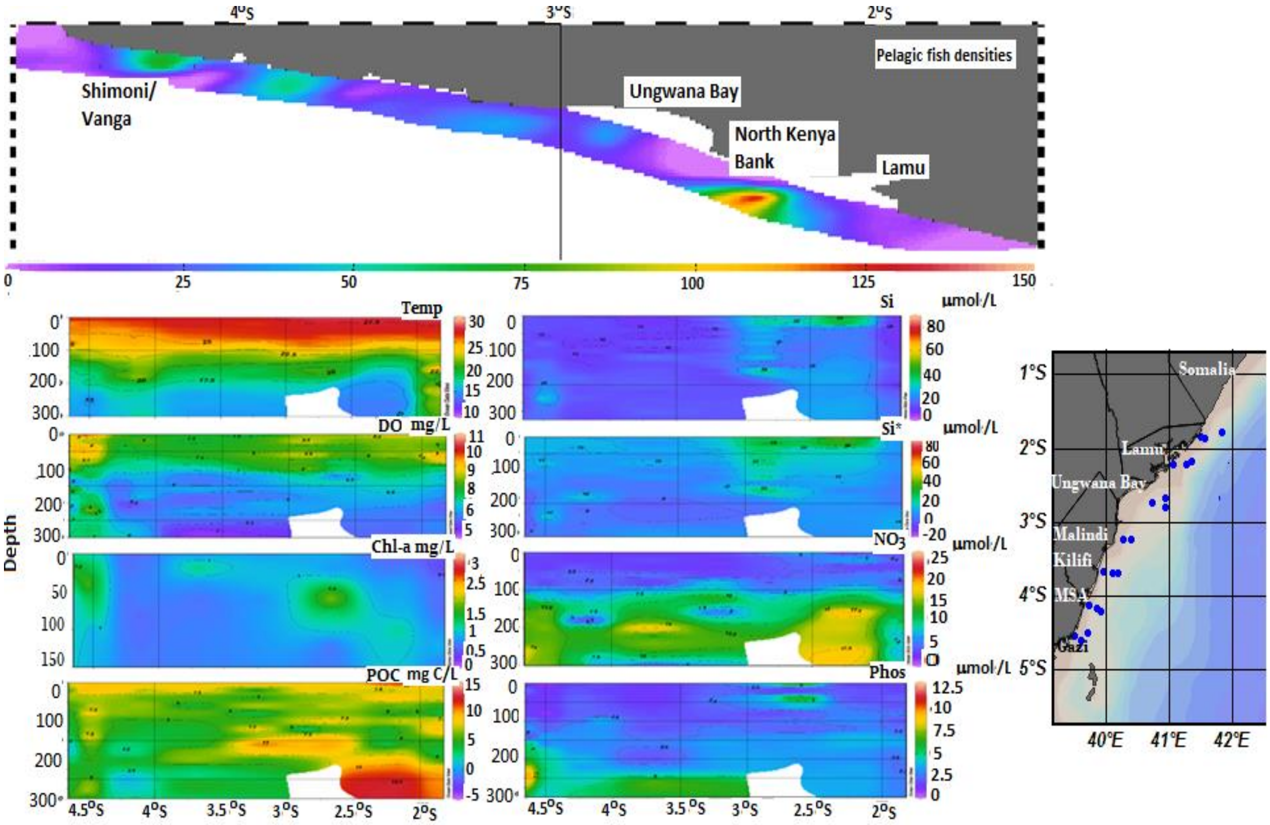

Figure 5. Vertical profiles showing physicochemical parameters, nutrient distribution and pelagic fish densities. The labeled map provides site information with latitude and longitude coordinates which provide insight on the actual location of the vertical profile plots.

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 $6.8{\times}10^6$ 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.

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