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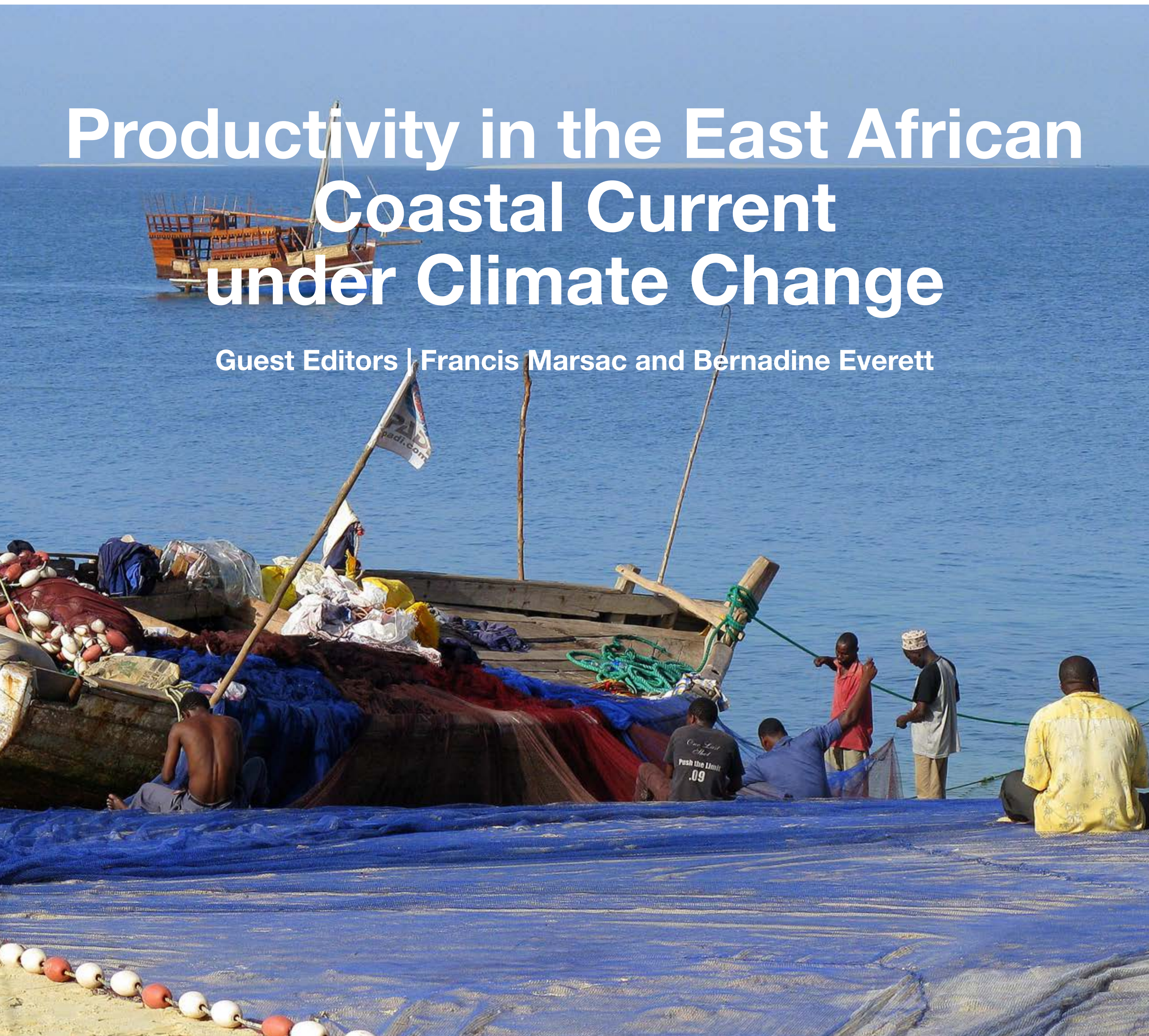

Productivity in the East African Coastal Current under Climate Change

Guest Editors | Francis Marsac and Bernadine Everett

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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?

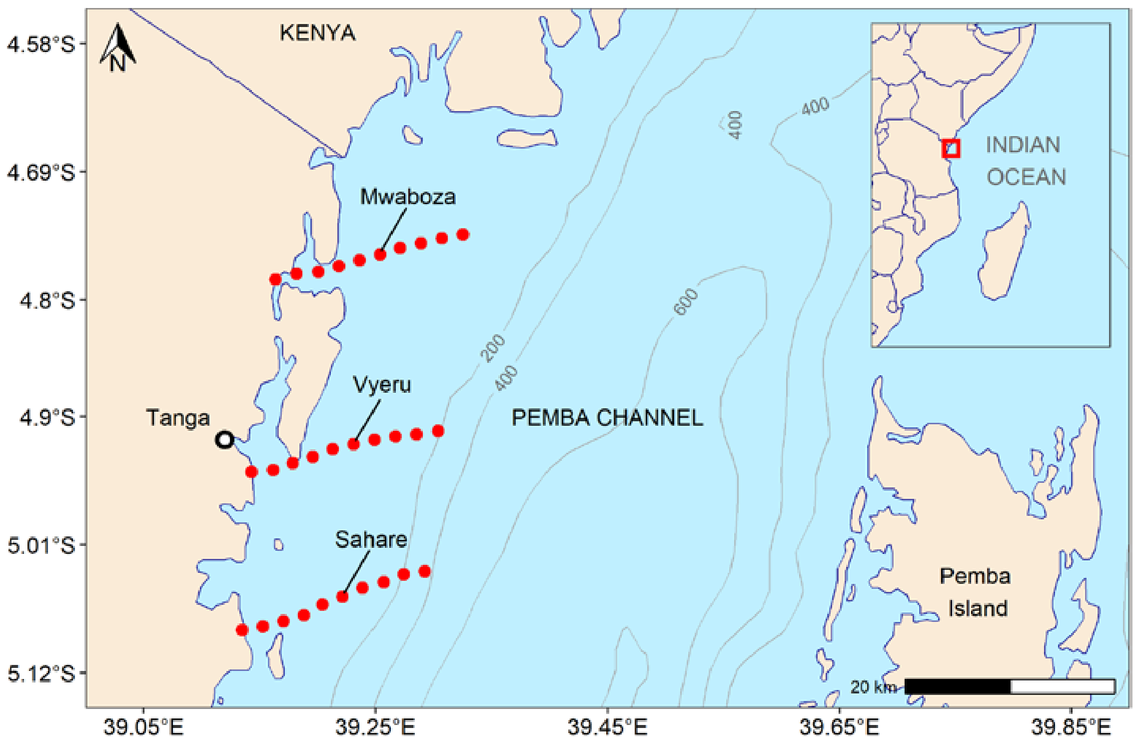

Figure 1. A map of the western Pemba Channel showing the study area. The inset map locates the study area in the Indian Ocean. Grey lines are isobars of 200 m interval contours. Red circles represent sampling stations along each transect.

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 0.45μm 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).

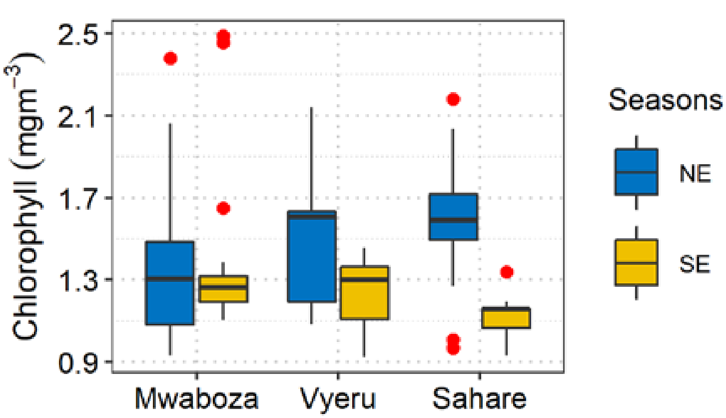

Figure 2. Chl-*a* concentration variation at Mwaboza, Sahare and Vyeru sites during the NE and SE monsoon seasons.

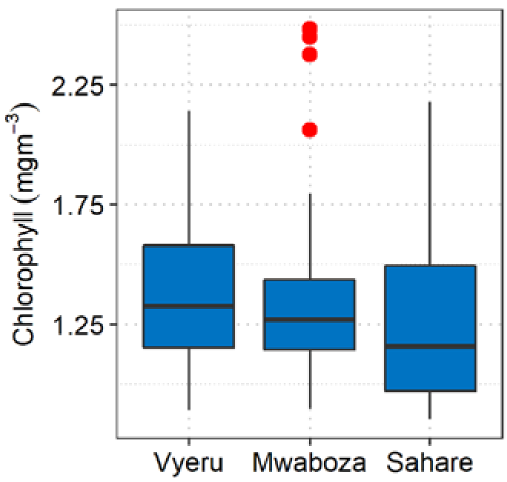

Figure 3. *In-situ* Chl-*a* variation at Vyeru, Mwaboza and Sahare with all seasons pooled together.

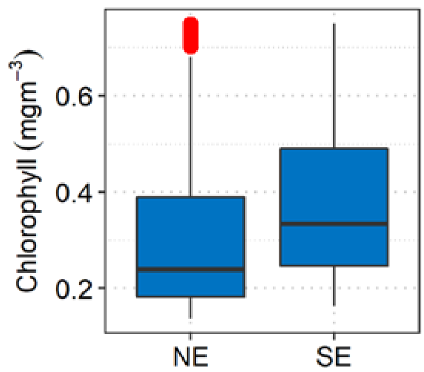

Figure 4. Satellite Chl-*a* concentration variation during the SE and the NE monsoon season within the study area.

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

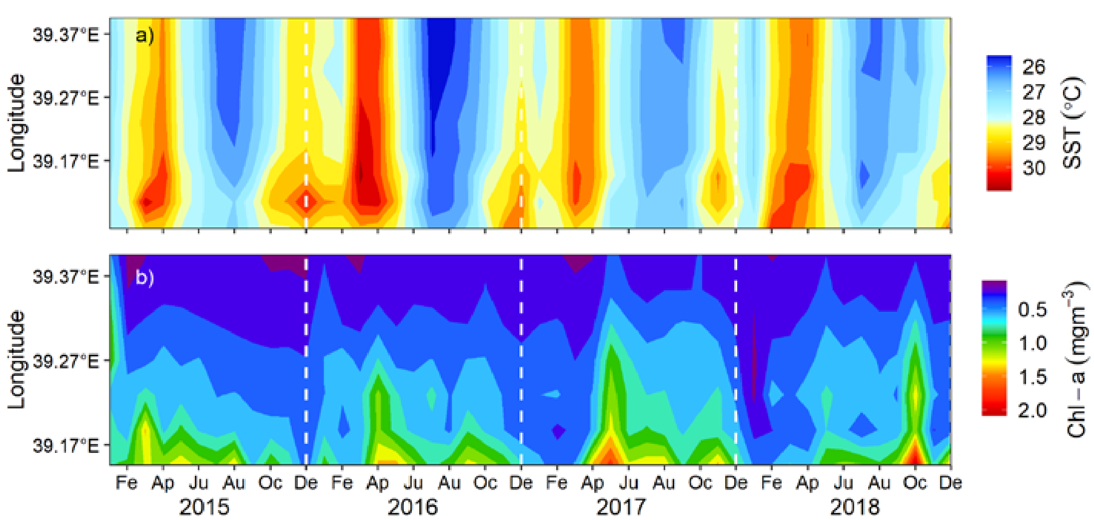

Figure 5. Monthly averaged longitude section hovmoler diagramme from satellite data: a) sea surface temperature, and b) satellite Chl-*a* concentration along the longitude between 5.1–4.64°S. White dotted line marks December—the last month of each year.

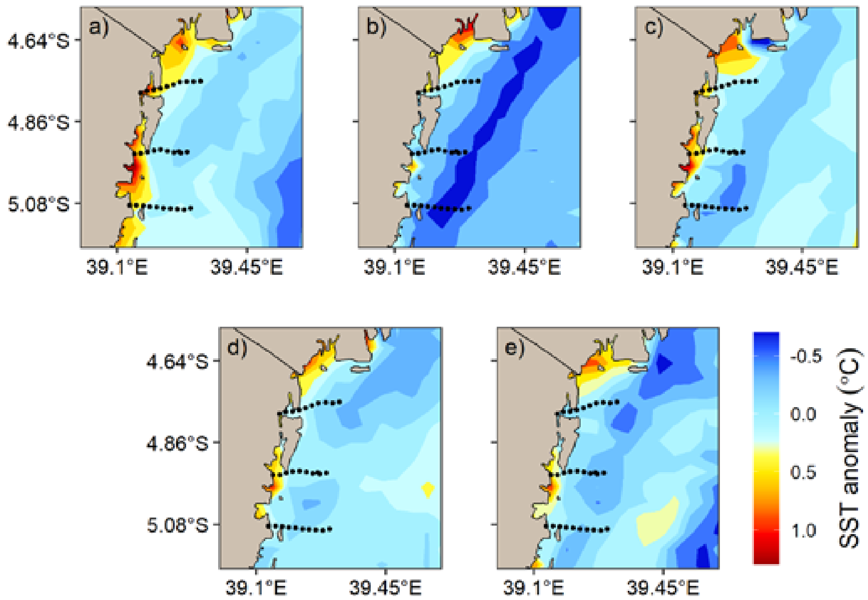

Figure 6. Climatological sea surface temperature anomalies for a) November, b) December, c) January, d) February, and e) March in the NE monsoon season.

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).

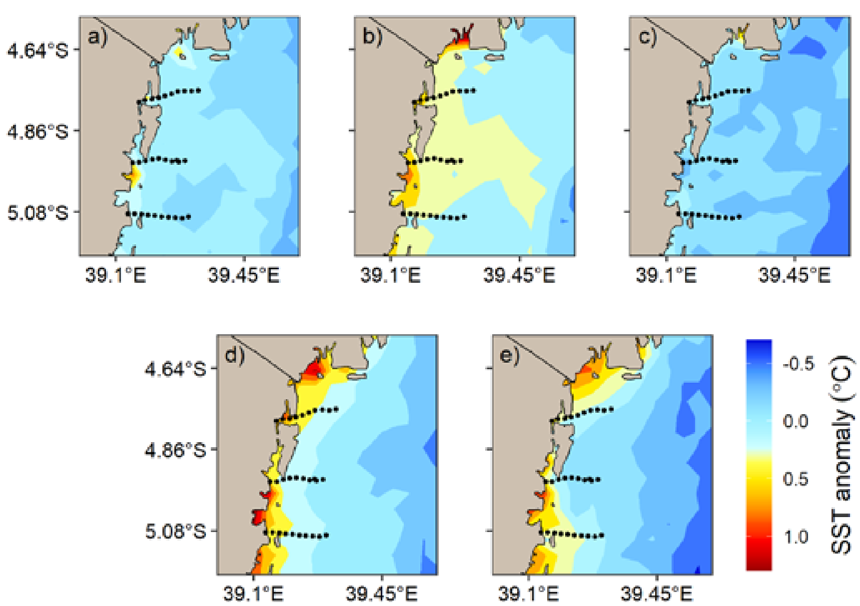

Figure 7. Climatological sea surface temperature anomalies for a) May, b) June, c) July, d) August, and e) September in the SE monsoon season.

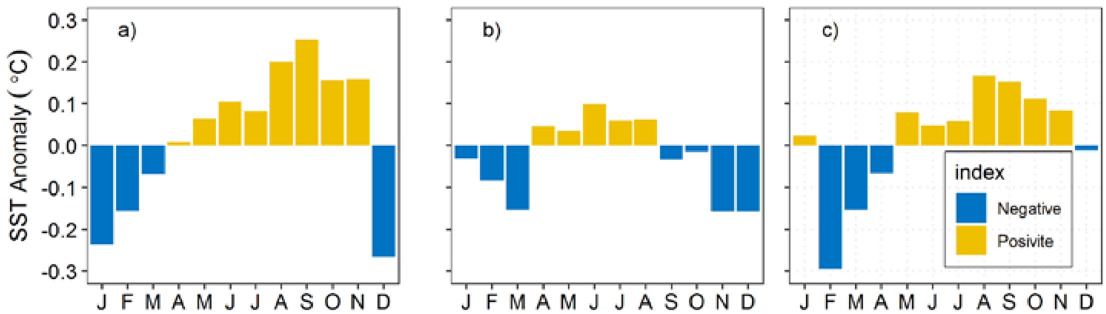

Figure 8. Seasonal cycles of computed sea surface temperature anomalies along three transects off Tanga. a) Mwaboza, b) Vyeru, and c) Sahare.

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

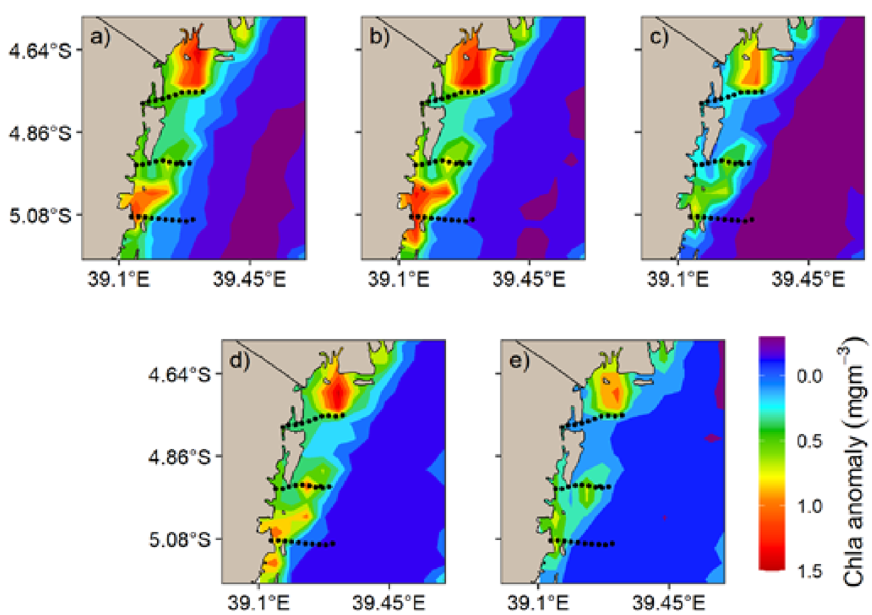

Figure 9. Climatological Chl-*a* concentration anomalies for a) May, b) June, c) July, d) August, and e) September in the SE monsoon season.

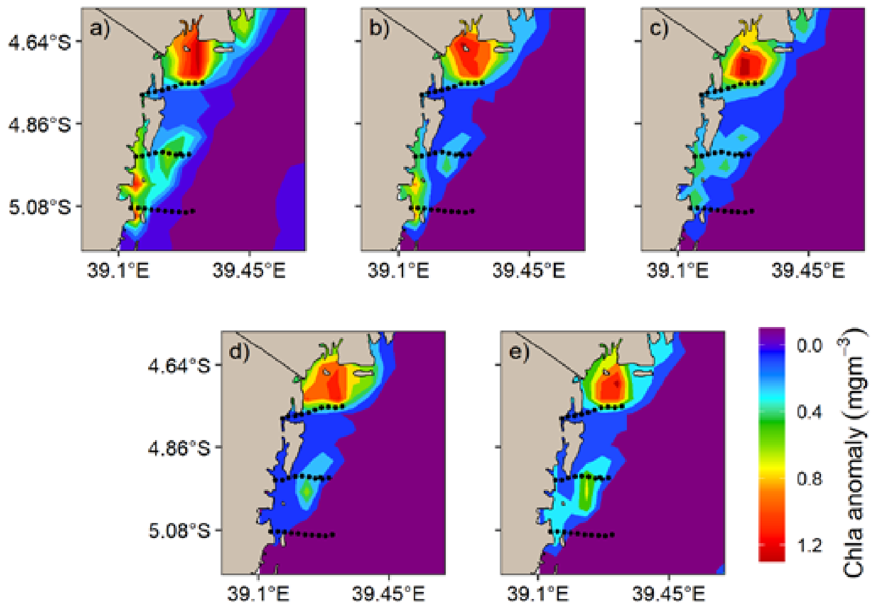

Figure 10. Climatological sea surface temperature anomalies for a) November, b) December, c) January, d) February, and e) March in the NE monsoon season.

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).

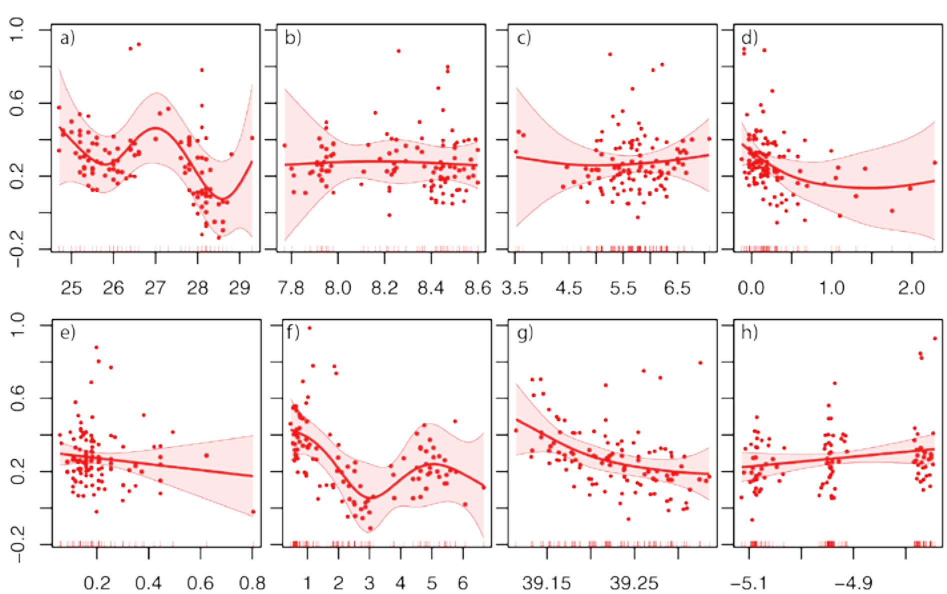

Figure 11. Residuals of the nonlinear terms estimated by means of GAM with smoothing splines for a) Temperature, b) pH, c) Dissolved Oxygen, d) Nitrate, e) Phosphate, f) Ammonium, g) Longitude, and h) Latitude.

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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