2018-12-11

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African Journals Online

https://doi.org/10.4314/wiojms.v17i2.3

Western Indian Ocean
JOURNAL OF
Marine Science

Volume 17 | Issue 2 | Jul – Dec 2018 | ISSN: 0856-860X

Chief Editor José Paula

Western Indian Ocean JOURNAL OF Marine Science

Chief Editor **José Paula** | Faculty of Sciences of University of Lisbon, Portugal

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Published biannually

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ISSN 0856-860X

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The influence of physical-chemical variables on the spatial and seasonal variation of Chlorophyll-*a* in coastal waters of Unguja, Zanzibar, Tanzania

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Abstract
Chlorophyll-a (Chl-a) concentrations were measured at four sites around Unguja, Zanzibar during the northeast (NE) and southeast (SE) monsoon seasons. Data for Chl-*a*, nitrate, phosphate, ammonia, dissolved oxygen, sea surface temperature, pH and salinity were collected once a month from March 2008 to March 2009. The SE monsoon had insignificantly higher Chl-*a* compared to the NE monsoon season when Chl-*a* for Bawe, Chumbe, Pongwe and Mnemba were combined ($W = 234$, $p = 0.93$). The drivers of high Chl-*a* during the SE monsoon were ammonia and nitrate. Results from individual sites showed that Pongwe and Mnemba had higher median Chl-*a* during the SE- than the NE monsoon season. Temperature, dissolved oxygen and ammonia were the major factors that influenced high Chl-*a* at these sites. In contrast, Chumbe and Bawe had higher median Chl-*a* during the NE- than the SE monsoon season. The major factors influencing high Chl-*a* in the NE at Chumbe and Bawe were high levels of nutrients, mainly from sewage effluent and various human activities around the coast in Zanzibar town. The interaction of Chl-*a* between monsoon seasons (NE and SE) and sites (Bawe, Chumbe, Pongwe and Mnemba) was insignificant ($F_{(1,3)} = 1.3144$, $p = 0.2949$). The principal component analysis revealed that different physical and chemical environmental variables affect Chl-*a* concentration over time and location.

Keywords: Chlorophyll-*a*, monsoon seasons, physical-chemical variables, Zanzibar

Introduction
Phytoplankton are microscopic single-celled or colony-forming organisms dwelling in the water column. They are free-floating organisms that depend entirely on water movement such as surface currents for their movement (Bryceson, 1977). They thrive in the euphotic zone; the upper water column of the world's oceans, lakes and rivers (Letelier *et al*., 2004). The euphotic zone receives energy from the sun that allows phytoplankton to photosynthesize; a chemical reaction that converts light energy into chemical energy (Letelier *et al*., 2004).

Phytoplankton play an important role in ecological processes, which influence the structure and function of food webs, nutrient cycling and the flux of particles to deeper waters (Sá *et al*., 2013). The distribution of phytoplankton in the euphotic zone varies both from the coastal to offshore areas (horizontal distribution), and from the surface to deeper waters (vertical distribution) (Barlow *et al*., 2007; Leal *et al*., 2009; Sá *et al*., 2013). There are several factors that govern these distributions including temperature, nutrients, irradiance, water column stability, internal waves, grazing, salinity and ocean currents (Barlow *et al*., 2007; Brunet and Lizon, 2003; Sá *et al*., 2013). These environmental factors are not homogenous, and hence the way they influence phytoplankton distribution differs from one place to the other, and from tropical to temperate ecosystems (Sá *et al*., 2013).

http://dx.doi.org/10.4314/wiojms.v17i2.3

Similar to terrestrial plants, phytoplankton contain Chl-*a*, an autotrophic component responsible for primary food production in aquatic systems (Limbu and Kyewalyanga, 2015). Boyce *et al.* (2010) affirmed that phytoplankton accounts for half of the production of organic matter on earth, hence serving as the primary source of food in oceans, rivers, seas and freshwater basins (Limbu and Kyewalyanga, 2015). The ecological role of Chl-*a* to convert light energy into food during photosynthesis attracted oceanographers to use it as an indicator of phytoplankton production and biomass (Baliarsingh *et al.,* 2015; Boyce *et al.,* 2010; Peter, 2013).

Some previous studies explored phytoplankton dynamics and distribution in the coastal waters of Tanzania. For example, Lugomela *et al.* (2002) studied the seasonal distribution of *Trichodesmium* species and found that *Trichodesmium* species follow a seasonal pattern with higher biomass during the NE monsoon compared to SE monsoon season. They also found that nitrate was higher in the NE than the SE monsoon seasons. Hamis and Mamboya (2014) explored the spatial and temporal variation of physico-chemical variables and phytoplankton at Ocean Road in Dar es Salaam, exposed to sewage discharge. They concluded that the sewer pipeline that drains the Dar es Salaam city center is the main cause of high nutrient levels in the area, which leads to higher phytoplankton biomass. Other studies like Barlow *et al.* (2011) investigated phytoplankton production and physiology in Unguja and Pemba Island, Zanzibar. They found that the phytoplankton communities are adaptable to changing environmental conditions. The availability of nitrates and phosphates were claimed as the primary factors that control the distribution of phytoplankton communities in Unguja and Pemba.

Most of these previous studies focused either on the distribution, diversity, and abundance of phytoplankton. Some looked at identification of phytoplankton species in the coastal waters of Tanzania (Lugomela, 1996; Bryceson, 1977). Other studies such as Hamis and Mamboya (2014) and Barlow *et al.* (2011) examined how sewage discharge and nutrient enrichment in coastal waters affect phytoplankton biomass. However, knowledge on how Chl-*a* concentration varies with monsoon season is poor. This study intended to fill this knowledge gap by exploring how Chl-*a* concentration varies with season (temporal) and space (spatial) along the coastal waters of Unguja Island, in relation to environmental factors.

Materials and methods

Study areas

This study was conducted in the coastal waters around Unguja Island, Zanzibar, Tanzania. The area is located between latitude 6.6 °S and 5.6 °S and longitude 39.15°E and 39.60°E (Fig. 1). Four study sites were selected for this study. The sites include Bawe, Chumbe, Mnemba and Pongwe. These study sites were chosen because of human activities that take place in these areas. While Bawe and Chumbe are found on the western side of Unguja Island, Pongwe and Mnemba are on the eastern side of the Island.

Like most western Indian Ocean countries, the coast of Tanzania is influenced by northerly and southerly monsoon winds (Nyandwi, 2013). From May to September the SE monsoon winds dominate and are usually strong and predominantly southerly (blowing from south to north) (Mahongo *et al.,* 2012), and this period is characterized by a mean sea surface temperature of 23°C (Semba *et al.,* 2016).

The NE monsoon winds are weaker and predominantly northerly (blowing from north to south), dominate from November to March, and this period is characterized by a mean sea surface temperature of 30°C (Semba *et al.,* 2016). April and October are the transition period when winds tend to subside (Mahongo and Shaghude, 2014). During this period of transition, there is a reversal in wind direction from the NE to the SE and vice versa (Mahongo *et al.,* 2012).

Furthermore, the island experiences two rainy seasons. The short rainy season is characterized by light rain and occurs around November and December. The heaviest and most prolonged rains occur between March and the end of May, with heavy rains throughout this period (Mahongo, 2015).

Data collection

Biological, physical and chemical variables at the selected study sites were recorded for the period of thirteen months between March 2008 and March 2009. At each study site, 5 l of surface water were collected in triplicate using plastic bottles for Chl-*a* determination. The samples were taken to the Institute of Marine Sciences for laboratory analysis. Water samples were filtered through 0.45μm pore size membrane filters followed by Chl-*a* extraction in 90 percent acetone overnight at 4 degree centigrade. The concentration of Chl-*a* was measured with a SHIMADZU spectrophotometer version UV-1201 following the method by Parsons *et al.* (1984). For nutrients, triplicate water samples were collected at each study site using a water sampler. Similar to Chl-*a*, phosphate, ammonia and nitrate were determined using a SHIMADZU spectrophotometer as documented in Parsons *et al.* (1984). A Hanna handheld instrument was used for in situ measurement of dissolved oxygen, pH, and temperature for each study site. An ATAGO refractometer was used to record *in situ* salinity values at each study site.

package to tidy the dataset structure and ensure each column formed a variable, and each row formed a measurement (Wickham and Henry, 2017). The tidy dataset was then transformed using the *dplyr* package (Wickham *et al.*, 2017). The *bind_ rows()* function from Wickham *et al.* (2017) was used to combine multiple variables (nitrate, phosphate, ammonia, dissolved oxygen, pH, salinity) by row, to form a single long format dataset.

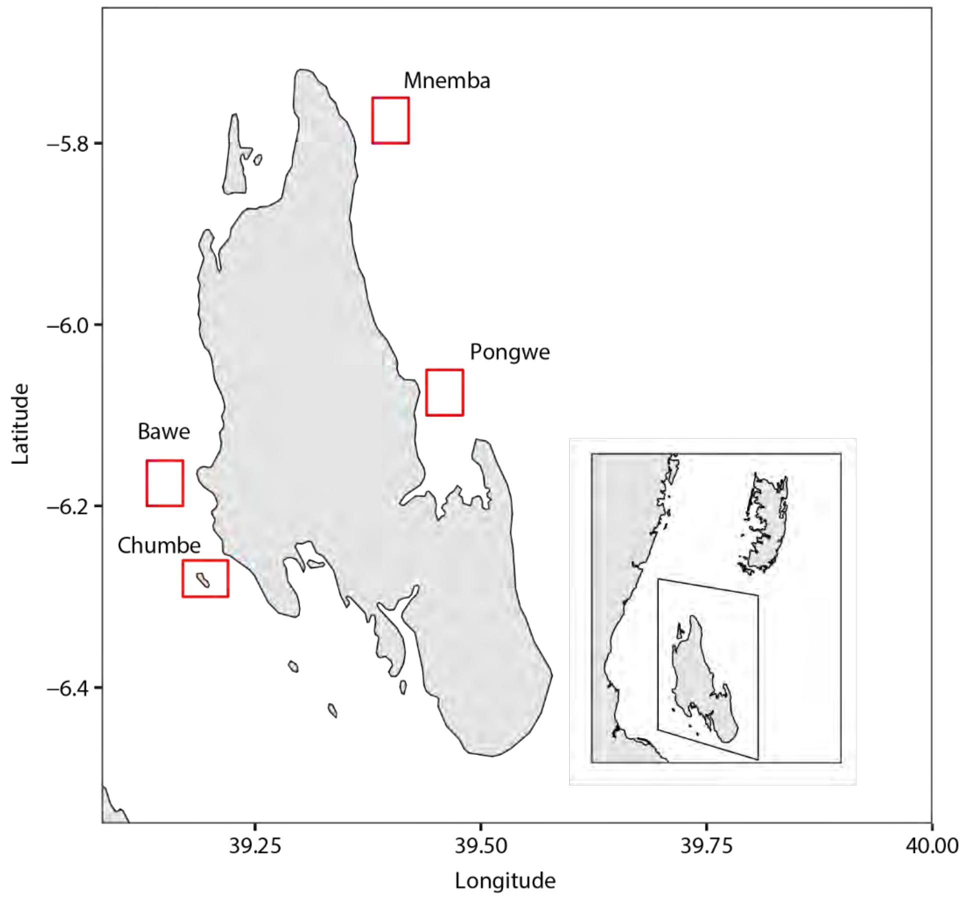

Figure 1. Map of Unguja Island showing the location of the study sites. The insert map indicates the location of Unguja Island in the Indian Ocean.

Data Processing

Data stored in a spreadsheet was imported and loaded into a data frame in R. Once the data was in R the format was ideal for tidying. Tidying is important because it puts the data in the correct format for different R functions. According to Wickham and Henry (2017), tidying data means storing it in a consistent form so that each column forms a variable, and each row forms an observation. Because the dataset was in a structure that limited the R functions, *spread()* and *gather()* functions were used in the *tidy*

Since environmental variables and Chl-*a* datasets were in separate data frames, The *full_join()* function was used to combine them, using key variables that were common to both datasets. The key variables included the station name and the date of sampling. The date of sampling was then separated to form year and month variables using *mutate()* in *lubridate* package (Grolemund and Wickham, 2011). The sampling months were used to determine the seasonality. Months between May and September were grouped into SE monsoon season, and months that fell between

November and March were grouped into NE monsoon season. April and October formed an intermediate season (inter-monsoon). The season variable was separated into *season* and *code* using the *separate()* function from the *tidyr* package (Wickham and Henry, 2017). The variable code was then dropped using the *mutate()* function in the *dplyr* package (Wickham *et al.,* 2017).

Data analysis

The aim of the analysis was to use the data to answer two key questions: the first was to assess if there was a difference in Chl-*a* between seasons (SE and NE) and among sampled sites; the second was to examine the drivers for the Chl-*a* variations. The Wilcoxon test was used to test the difference in median Chl-*a* between the NE and SE monsoon season.

The seasonal mean and standard deviation for each sampled site was computed to determine sites with high and low Chl-*a* concentrations. The computation was chained in *markdown* using the function in the *dplyr* package as described by Wickham *et al.* (2017). The statistics for the inter-monsoon season was dropped and the mean and standard deviation computed for Chl-*a* concentration, and the statistics by site and season were grouped.

The distribution of the data was tested using a histogram. Data that was not normally distributed was then transformed. The type of transformation method applied depended on the skewness of the data itself. According to Wickham *et al.* (2017), logarithmic transformation is used for variables with skewness values between 0.5 and 1, and square root transformation is appropriate for variables with skewness values of greater than 1, and no transformation is required for variables with skewness values below 0.5. Chl-*a* values were transformed for Bawe, Chumbe and Mnemba using square root transformation because their skewness values were greater than 1. The Shapiro test was used for groups as described by Millard (2013), to test for normality of transformed Chl-*a*. Because the samples in the current study were unbalanced (all months were sampled once, except for March, which was sampled twice in both 2008 and 2009), unbalanced two-way ANOVA was used to infer the difference between seasons and among sites. *Anova ()* in the *car* package was used for computation of two-way ANOVA for unbalanced designs (Fox and Weisberg, 2011). Before running the two-way ANOVA function, the Chl-*a* dataset was randomly sampled using the *sample_ n()* function (Wickham *et al.,* 2017).

Principal component analysis (*prcomp()* in R) was used to assess the drivers that influence the Chl-*a* variation. These include dissolved oxygen, pH, salinity, temperature, ammonia, nitrate and phosphate. Because *prcomp()* requires all rows to have values, the data was first cleaned by dropping all rows with NA using the *dplyr* package (Wickham *et al.,* 2017). The *prcomp()* function from R Core Team (2017) was then used to compute the principal component. For seasonality, the data were filtered into seasons in order to make a biplot of separate seasons. The *factoextra* package as described by Kassambara and Mundt (2017) was then used to visualize the drivers and their influence on Chl-*a*.

Results

In respect to seasonality, the southeast monsoon season had a median Chl-*a* concentration of 0.35 mg/m^3 as compared to 0.32 mg/m^3 for northeast monsoon season (Table 1). These results suggest that the SE monsoon has a relatively higher Chl-*a* concentration than the NE monsoon season. However, when the mean Chl-*a* concentration is considered, the results reveal that the NE season has a higher mean Chl-*a* (0.41 mg/m^3) than the SE monsoon season (0.36 mg/m^3). The high value of Chl-*a* during the NE season is contributed by the outliers of the samples collected during this season (Figure 2). However, the difference in the median of Chl-*a* between the two seasons was insignificant (W = 248, p = 0.86)

During the SE monsoon, Pongwe had a relatively higher Chl-*a* concentration (0.378 mg/m^3), followed by Mnemba, Bawe and Chumbe, which had the lowest of 0.251 mg/m^3 (Table 2). However, during the NE monsoon, the Chl-*a* concentration differed, with Bawe having relatively a higher Chl-*a* concentration (0.477

Table 1. Summary statistics of Chlorophyll-*a* with season.

Seasons	Min	Max	Median	Mean	STD
NE	0.094	0.886	0.324	0.413	0.211
SE	0.143	0.644	0.350	0.357	0.115

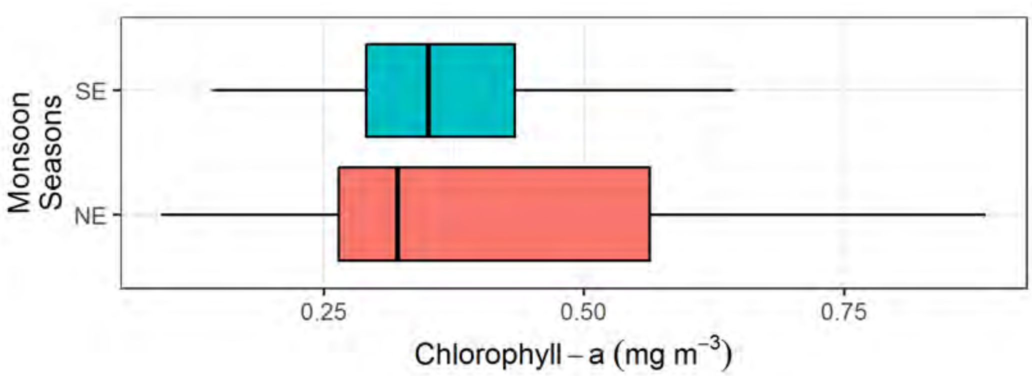

Figure 2. A boxplot showing variations in Chlorophyll-a concentration between monsoon seasons.

mg/m^3) followed by Chumbe, Pongwe and finally Mnemba, which had the lowest Chl-*a* concentration of 0.279 mg/m^3 (Table 3).

The boxplot shows that Mnemba and Pongwe had higher median Chl-*a* concentrations during the SE than the NE monsoon season (Fig. 3, Table 2). In contrast, Chumbe and Bawe had higher median Chl-*a* concentrations during the NE than the SE monsoon season (Fig. 3, Table 3). The results suggest that Chl-*a* concentration varied both in time (season) and space (study sites).

Since the statistic used to test for Chlorophyll-*a* and other chemical and physical variables were required to fit the normal distribution, the nature of the distribution of the data was explored prior to analysis. The results showed that combining the Chl-*a* data for all sites made the data unfit for normal distribution (GroupTest, p = 0.0028). However, observing the distribution at each site showed that Chl-*a* at Pongwe was normally distributed (p = 0.92), and the other study sites were not (p < 0.05). Normal distribution for Chl-*a* for Bawe, Chumbe and Mnemba sites was achieved after square root transformation (z = -1.25, p = 0.105).

The ANOVA table shows that the difference in mean Chl-*a* concentration between the Bawe, Chumbe, Mnemba and Pongwe sites was insignificant ($F_{(1,3)}$=1.55, p = 0.23). Similarly, the mean difference in concentration of Chl-*a* between the NE and SE monsoon seasons was not significant ($F_{(1,1)}$ = 1.14, p = 0.29). The interaction of mean Chl-*a* between study sites and seasons was also insignificant ($F_{(1,3)}$=1.31, p = 0.29). The results of the two-way ANOVA indicate that the spatial and temporal effects have little influence on Chl-*a* concentration.

Table 2. Summary statistics of Chlorophyll-a concentration during the southeast monsoon season for the four study sites.

Sites	Seasons	Min	Max	Median	Mean	STD
Pongwe	SE	0.355	0.644	0.378	0.447	0.123
Mnemba	SE	0.143	0.447	0.346	0.339	0.121
Bawe	SE	0.240	0.497	0.341	0.364	0.103
Chumbe	SE	0.222	0.368	0.251	0.277	0.061

Table 3. Summary statistics of Chlorophyll-a concentration during the northeast monsoon season for the four study sites.

Sites	Seasons	Min	Max	Median	Mean	STD
Bawe	NE	0.286	0.758	0.477	0.492	0.183
Chumbe	NE	0.218	0.791	0.349	0.426	0.214
Pongwe	NE	0.094	0.676	0.294	0.359	0.220
Mnemba	NE	0.226	0.886	0.279	0.376	0.252

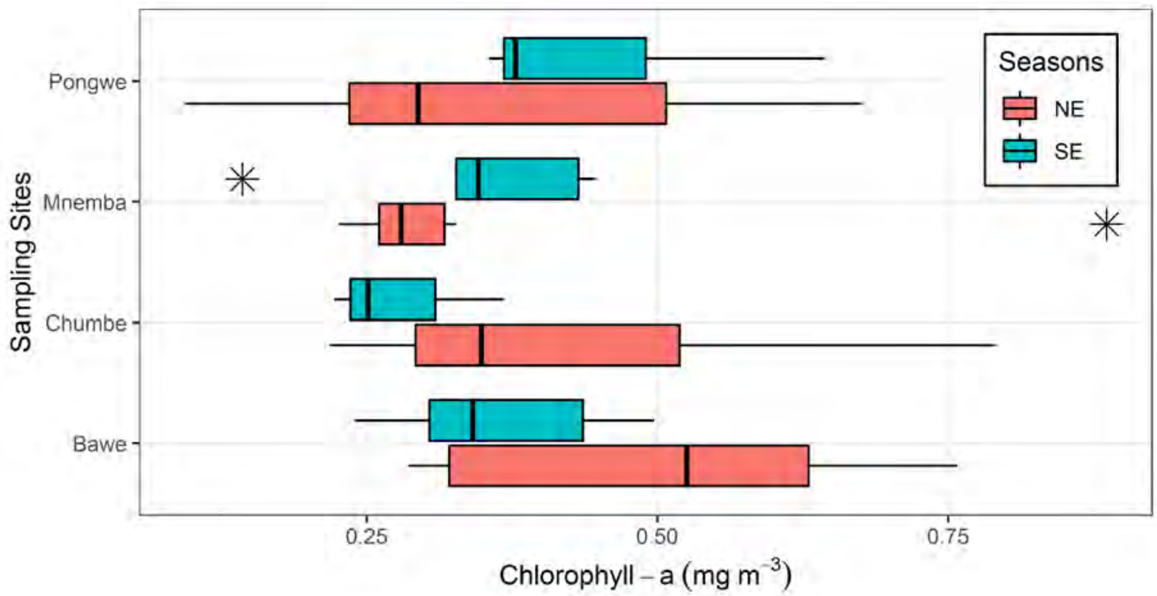

Figure 3. Boxplot showing Chlorophyll-a concentration variation with study sites and seasons.

Drivers of Chlorophyll-*a* variation

When the Principal Component Analysis (PCA) was run for all seasons together, it was found that in dimension 2 (Dim2), ammonia, nitrate, phosphate, Chl-*a*, pH, and temperature displayed negative coefficients, while dissolved oxygen and salinity displayed positive coefficients (Fig. 4). This shows that Chl-*a* had a positive linear relationship with ammonia and nitrate during the SE monsoon season, while phosphate, pH and temperature showed a positive relationship during the NE monsoon season. On the other hand, Chl-*a* had a negative linear relation with dissolved oxygen in the SE monsoon season, and salinity in the NE monsoon season.

However, when the NE monsoon season data was analysed on its own, it was found that in Dim2, ammonia, temperature, dissolved oxygen, pH, phosphate, nitrate and Chl-*a* displayed negative coefficients, whereas salinity displayed a positive coefficient (Fig. 5). The ellipse indicates that chlorophyll had a positive linear relationship with ammonia, nitrate, phosphate, dissolved oxygen, pH, and temperature at Chumbe, Bawe and Mnemba, and a negative linear

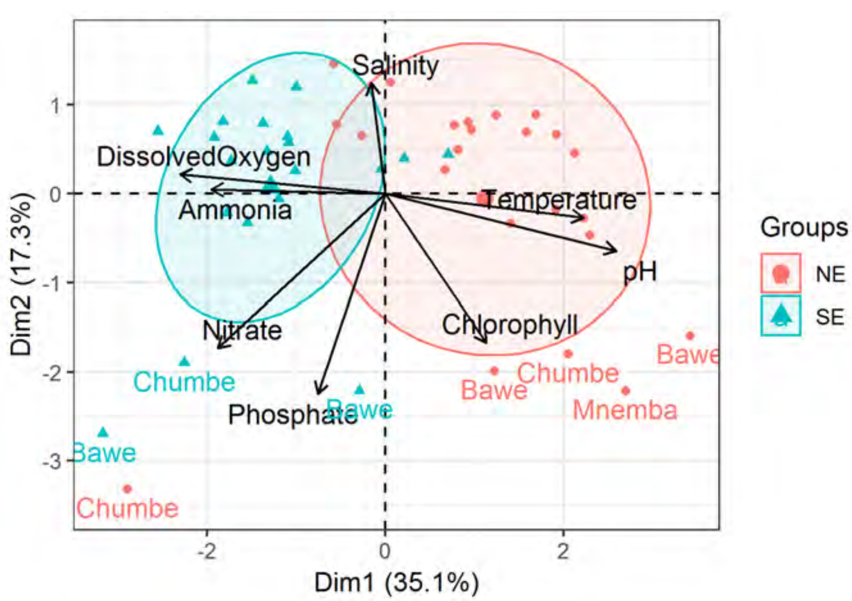

Figure 4. Biplot for combined northeast and southeast monsoon seasons at Bawe, Chumbe, Mnemba and Pongwe.

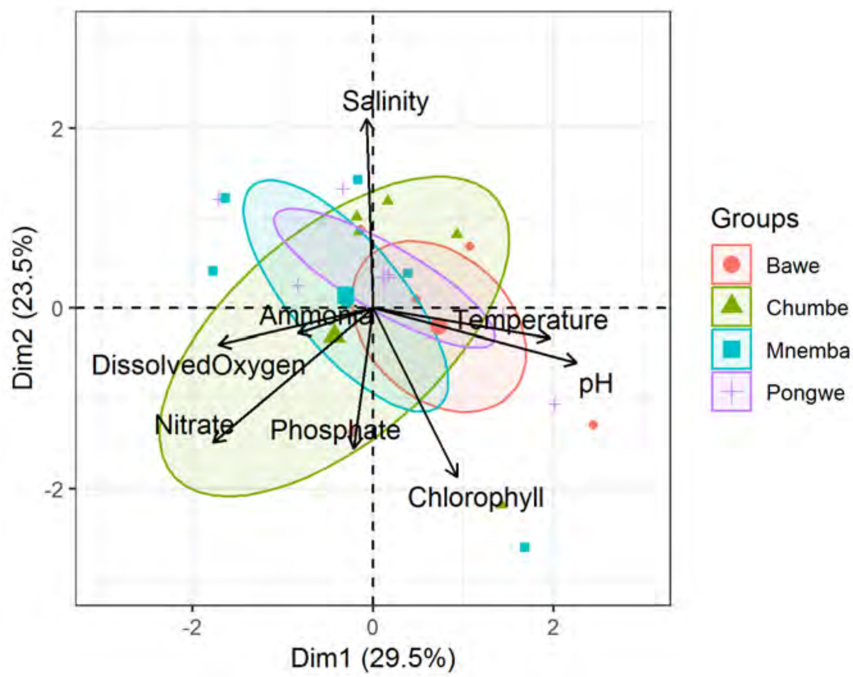

Figure 5. Biplot for northeast monsoon season at Bawe, Chumbe, Mnemba and Pongwe.

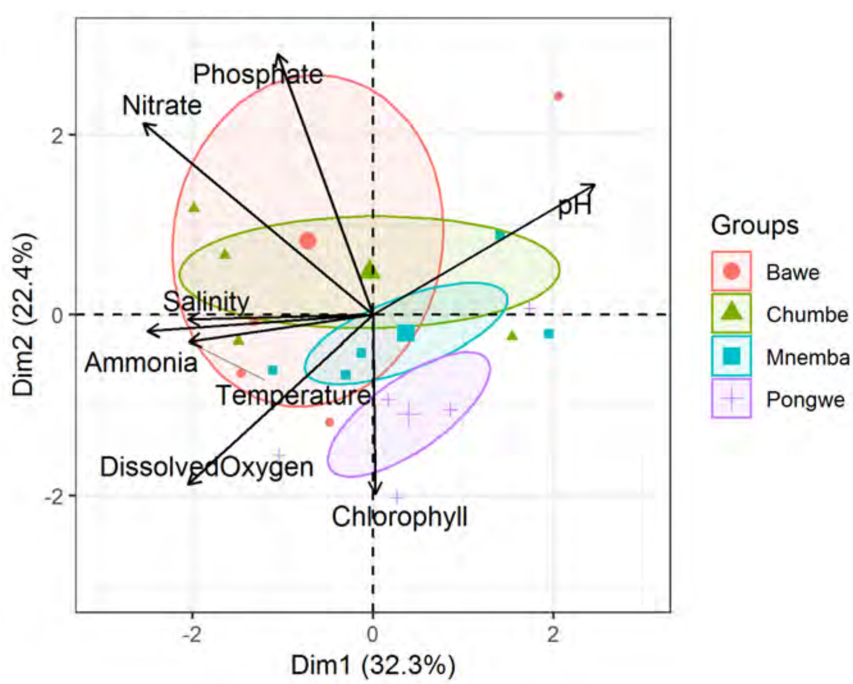

Figure 6. Biplot for southeast monsoon season at Bawe, Chumbe, Mnemba and Pongwe.

relation with salinity at Bawe, Chumbe, Pongwe and Mnemba during the NE monsoon.

Likewise, when data for the SE monsoon season were analyzed, it was found that in Dim2, ammonia, temperature, dissolved oxygen, and salinity, as well as Chl-*a* displayed negative coefficients, whereas nitrate, phosphate and pH displayed positive coefficients (Fig. 6). While ecllipses for Pongwe and Mnemba fall on negative coefficients, Chumbe and Bawe are on positive coefficients in Dim2. The figure indicates that chlorophyll had a positive linear relationship with ammonia, temperature, dissolved oxygen and salinity at Mnemba and Pongwe, and a negative linear relation with nitrate, phosphate, and pH at Bawe and Chumbe during the SE monsoon.

Discussion

Until now, there has been limited information on how Chl-*a* concentration varies in both space and time in the coastal waters of Zanzibar. This study has attempted to fill this gap by assessing Chl-*a* concentration at four selected sites during the SE and NE monsoon seasons. Previous studies have documented that the pattern of Chl-*a* concentration in the coastal water of Tanzania is associated with seasonal changes (Semba *et al.,* 2016; Peter, 2013). McClanahan (1988) reported that the coastal waters have relatively higher Chl-*a* concentrations during the SE monsoon as compared to the NE monsoon season. Similar seasonal patterns for Chl-*a* were found in this study as in Semba *et al.* (2016), Peter (2013), and McClanahan (1988) (Fig. 2). The SE monsoon had a median of 0.350 mg/m^3 Chl-*a* concentration compared to 0.324 mg/m^3 in the NE monsoon season. The SE season had a concentration of about 0.026 mg/m^3 higher than the NE season. However, the difference in median concentration of Chl-*a* between the NE and SE season was not significant ($W = 234$, $p = 0.93$).

The median concentration of Chl-*a* at individual sites showed a seasonal pattern. For example, there was a higher Chl-*a* concentration during the SE as compared to the NE monsoon season at Mnemba and Pongwe (Fig. 3, Table 2). In contrast, Chumbe and Bawe showed the opposite, having water of higher median Chl-*a* concentration during the NE as compared to the SE monsoon season (Fig. 3, Table 3). This difference in Chl-*a* concentration can be attributed to the location on the island. For example, Pongwe and Mnemba are distant from Zanzibar town, where there is little influence from human activities. The findings from Mnemba and Pongwe sites match the seasonal pattern of Chl-*a* found in previous studies (Semba *et al.,* 2016; McClanahan, 1988; Peter, 2013) that the SE season has higher Chl-*a* concentrations than the NE monsoon season; a characteristic widely experienced in the western Indian Ocean. The findings at Bawe and Chumbe Island is contrary to what is widely understood with regards to seasonal Chl-*a* concentration. The possible reason for this pattern might be due to the contribution of sewage inflow, the presence of the port, uncontrolled tourist activities, and fishing activities.

The waste water from Unguja Island is discharged into the ocean in the Zanzibar Channel. Because the current flows past Bawe and Chumbe Island (Nyandwi, 2013), nutrients in this waste water may affect these sites through stimulating localised phytoplankton growth. Nyandwi (2013) studied ocean circulation across the Zanzibar Channel and found that current velocity and direction is north easterly during the SE monsoon, but is reversed during the NE monsoon period. The reversal of the current during the NE monsoon season allows wastewater discharged from Zanzibar town to reach Chumbe and Bawe islands in Zanzibar channel. This suggests nutrient rich waters from Zanzibar town flow in a south westerly direction during the NE monsoon season, impacting the areas around Bawe and Chumbe islands, and enhancing primary production during the NE monsoon.

Although the difference in Chl-*a* concentration between the NE and SE monsoon seasons and among sites were insignificant ($F_{(1,3)} = 1.3144$, $p = 0.2949$), principal component analysis uncovered how environmental variables, which vary with season, influenced Chl-*a* concentration within the study sites (Fig. 4). Ammonia, phosphate and nitrate were found to be the dominant contributor to high Chl-*a* at Chumbe and Bawe during the NE monsoon season (Fig. 5). Ammonia, temperature, and dissolved oxygen were the dominant contributor to high Chl-*a* at Pongwe, Bawe and Mnemba during the SE monsoon season (Fig. 6). Surprisingly, nitrate and phosphate contribute negatively to Chl-*a* concentration during the SE monsoon season (Fig. 6).

Generally, environmental variables affect Chl-*a* concentration in time and space. The median Chl-*a* was insignificantly higher during the SE as compared to the NE monsoon season. While ammonia and nitrate were the main contributors to high Chl-*a* concentration in the SE monsoon season, pH, temperature and phosphate affected the amount of Chl-*a* in the NE monsoon season. Based on site-season interaction, ammonia, phosphate and nitrate had major influences on high Chl-*a* at Chumbe and Bawe during the NE monsoon season. In contrast, temperature, dissolved oxygen and ammonia affected Chl-*a* concentration at Pongwe, Mnemba and Bawe during the SE monsoon season. Since Chl-*a* is used as the proxy for phytoplankton biomass, understanding how these microscopic plants change over time and space is important, because any change in Chl-*a* concentration affects other marine organisms, and ecosystems in general.

Acknowledgements

We would like to thank the Global Environment Facility (GEF) for the financial support of this work through the Coral Reef Targeted Research and Capacity Building for Management (CRTR) project. We would like to acknowledge Mr. Samwel Limbu from University of Dar es Salaam for his support and contributions during the field and laboratory work. Dr. Salim M. Mohammed and Dr. Musa Chacha from the Institute of Marine Sciences (IMS) are highly acknowledged for sharing nutrient data. We also owe a special note of gratitude to Technicians, Mr. Mtumwa Mwadini and Ms. Khayrat Ubwa, for their technical support during the field and laboratory work.

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