Spatial distribution of surface chlorophyll *a* and micro-phytoplankton density and diversity around two islands and at two banks of the Mascarene region

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Abstract

The present study validated the use of AquaMODIS sea surface chlorophyll *a* (Chl*a*) concentrations and investigated the spatial variation in density and diversity of micro-phytoplankton around two islands and two fishing banks of the Mascarene region. The study included areas around Mauritius (MRU) and Rodrigues (ROD) Islands, at Nazareth (NZ) Bank, and in the Joint Management Area (JMA) between the Republic of Mauritius and the Republic of Seychelles, more specifically at the Saya de Malha (SM) Bank. The AquaMODIS data were based on 67 match-up data points of *in-situ* against satellite Chl*a* concentrations. The micro-phytoplankton community structure was investigated by determining the density variation and using the Shannon Wiener (H') and Evenness (E_{var}) diversity indices. The satellite and *in-situ* Chl*a* data were significantly and positively correlated when pooled for the four sites studied (R^2 = 0.441; r = 0.642, $P < 0.01$), and when analysed separately for islands (R^2 = 0.480; r = 0.694), and banks (R^2 = 0.233; r = 0.483). However, the Chl*a* satellite values tended to be lower than the *in-situ* Chl*a* data. The highest densities of micro-phytoplankton were observed in the eastern and northern regions for MRU and ROD, respectively. The most dominant genera of micro-phytoplankton were *Coscinodiscus*, *Navicula, Chaetoceros* and *Ceratium*. The Shannon-Wiener diversity index values for diatoms were all above 2.5 with waters around the islands having higher diversity compared to the banks. Overall, the different micro-phytoplankton around the islands, except for the group of cyanobacteria at ROD Island, were more evenly distributed ($E_{var} > 0.6$) compared to the banks. This study indicated that AquaMODIS Chl*a* satellite data is valid and may be potentially used as a proxy for *in-situ* Chl*a* concentration on the Mascarene Plateau. The results of this study also provide detailed insight into the spatial variation in micro-phytoplankton density and diversity on the Mascarene Plateau in the Western Indian Ocean. Further long-term studies are warranted to thoroughly understand the temporal (including seasonal and inter-annual) variations in Chl*a* and micro-phytoplankton distribution for adequate and appropriate management of these ocean territories.

Keywords: Exclusive Economic Zone, Joint Management Area, micro-phytoplankton, fishing banks, AquaMODIS, Republic of Mauritius, Republic of Seychelles

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Introduction

The Exclusive Economic Zone (EEZ), as defined by the United Nations Convention on the Law of the Sea (UNCLOS), is an area beyond and adjacent to the territorial sea of a coastal State having the sovereign rights for the purpose of exploring, exploiting, conserving and managing its natural resources. The EEZ of the Republic of Mauritius is vast (Fig. 1a). the Mascarene Plateau in the Western Indian Ocean is reputed for its fishing banks which have both economic and ecological importance (Sala *et al*., 2016). The Saya de Malha Bank (SM) (35,000 km^2), a jointly managed area by the Republic of Mauritius and Seychelles, is one of the major fishing banks of the world (WWF, 2011). Being a fairly challenging region to access by local scientists, the use of remote sensing for SM and Nazareth Bank (NZ) may prove to be a very convenient tool in providing important datasets over these vast sea areas (Shi and Wang, 2018).

Researchers all around the world are turning towards the use of satellite imaging to access biological and physical data of the ocean, especially for remote areas (Shi and Wang, 2018). Access to and acquisition of a vast range of scientific data (for instance, Chl*a* concentration, sea surface temperature and nutrients via modelling of reflectance data) (Wang *et al*., 2018), from any corner of the world has been possible using remote sensing (Colomina and Molina, 2014), even from regions that were previously inaccessible due to high traveling costs, dangers or other reasons (Zhu *et al*., 2018). Managing a vast area of the ocean can sometimes prove to be very costly and time-consuming. Hence, using remotely sensed data, for example to estimate sea surface Chl*a* concentration, can be used to predict the estimated productivity of a specific area of the ocean and monitor its change over time.

One of the most studied parameters in the ocean using remote sensing is Chl*a* concentration. Several studies on satellite-derived and *in-situ* chlorophyll distribution linked to phytoplankton density have been conducted. Numerous studies have indicated that the abundance of phytoplankton is directly proportional to the level of Chl*a* in the sea water (Felip and Catalan, 2000; Lyngsgaard *et al*., 2017) and this is explained by the fact that the Chl*a* molecule is present in all phytoplankton communities. Chl*a* as an estimate of phytoplankton abundance and temperature can be used as a sound basis to determine the productivity around fishing banks and other parts of the ocean (Townsend and Thomas, 2001). Generally, the higher the primary productivity, the higher will be the abundance of fish in an area (Capuzzo *et al*., 2018; Stock *et al*., 2017). Moreover, several studies have been conducted using various satellites such as MODIS-Aqua and SeaWiFS each having different accuracy levels, spatial and temporal resolutions, where the coefficient of determination (R^2 value) is usually used to determine the validity of the use of satellite Chl*a* concentrations (Deidun *et al*., 2011; Fleming and Korb, 2004; Wozniak *et al*., 2014) but requires ground truthing against *in situ* measurements. The aim of this study is to attempt the statistical comparison of MODIS ocean colour data, for a near-shore marine area off the north-east coastline of Malta, with *in situ* surface chlorophyll-a measurements, and to extract a twelve-month ocean colour data series for the same marine area. Peaks in surface chlorophyll-a concentration occurred in the January-February period, with lowest values being recorded during the early spring period. Log bias values indicate that the MODIS dataset under-estimates the surface chlorophyll-a values, whilst RMSD and R^2 values suggest that the match-up between satellite and *in situ* values is only partly consistent.". Around 60-78 % of the global ocean area has oligotrophic waters with Chl*a* concentrations of ≤0.25 mgm^{-3} (Armengol *et al*., 2019). A novel algorithm by Hu *et al*. (2012) has enabled scientists to use satellite extracted sea surface Chl*a* with an acceptable level of accuracy even if the waters are oligotrophic. It is now possible for scientists to determine the variability of ocean surface Chl*a* and to use this information as an index to determine primary productivity/phytoplankton biomass, both on small and large scales (Jacox *et al*., 2015; Lee *et al*., 2015).

In the Western Indian Ocean (WIO), Devassy and Goes (1991) assessed the variability of *in-situ* phytoplankton community assemblage in the EEZ of Mauritius through an oceanographic survey conducted almost two decades ago in September-October 1987. More recent micro-phytoplankton studies around MRU have also been conducted *in-situ* by Moodoosoodun *et al*. (2010) at a Marine Protected Area (MPA), Sadally *et al*. (2014a, 2015, 2016) and Sandooyea *et al*. (2020) at coral reefs and other coastal marine ecosystems, Sadally *et al*. (2014b) at a channel-based marine fish aquaculture site, and Armance *et al*. (2019) and Soondur *et al*. (2020) at a barachois-based oyster farm. Badal *et al*. (2009) used satellite global ocean color data to locate eddy formation in the South West

Mascarene Plateau while Ramchandur *et al.* (2017), using satellite data, documented the variability in Chl*a* and sea surface temperature at the NZ. However, very few studies have attempted to validate the use of satellite data by looking at *in-situ* and satellite Chl*a* and micro-phytoplankton density and diversity aspects simultaneously on the Mascarene Plateau in the WIO.

This study attempts to provide further data on Chl*a* and micro-phytoplankton from the Mascarene region which is known to be data deficient, though SM is an area of high ecological and economic importance. Therefore, the aim of this study was to validate satellite sea surface Chl*a* concentration data using *in-situ* Chl*a* data on the Mascarene Plateau. The objectives were to: (1) determine the in-situ sea surface Chl*a*

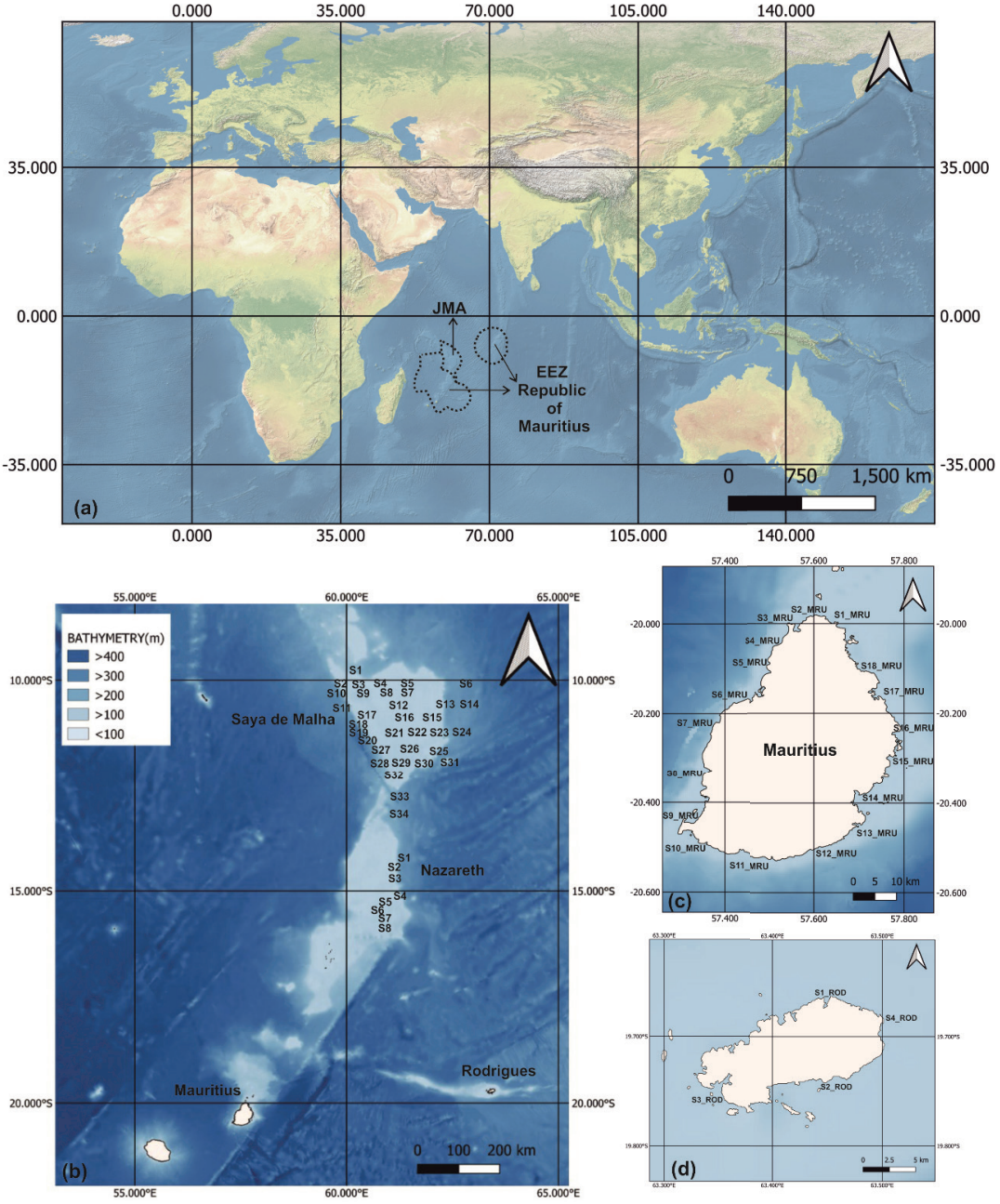

Figure 1. The world map indicating the EEZ (Exclusive Economic Zone) of the Republic of Mauritius and JMA (Joint Management Area) between the Republic of Mauritius and Republic of Seychelles. (a) EEZ and JMA boundaries; (b) the four study areas namely Saya de Malha (34 stations) and Nazareth (8 stations) Banks, Mauritius and Rodrigues Islands with indicative range of bathymetry data; (c) Mauritius Island (MRU) with the 18 stations and; (d) Rodrigues Island with 4 stations where station is referred to as "S".

concentration in four regions namely Maurituis Island (MRU), Rodrigues Island (ROD), Saya de Malha Bank (SM), and Nazareth Bank (NZ); (2) correlate *in-situ* Chl*a* data with AquaMODIS satellite sea surface Chl*a* concentrations; and (3) evaluate the density and diversity of micro-phytoplankton in the four studied regions.

Methodology

Site and stations

This study focused on four regions including MRU, ROD, and the two fishing banks SM and NZ were included in the study. ROD is located around 600 km from MRU, while SM and NZ are around 1175 km offshore from MRU. Eighteen stations (station is referred as 'S' throughout this paper) were established around MRU: S1_MRU - S18_MRU (Fig. 1c); 4 stations around ROD: S1_ROD - S4_ROD (Fig. 1d); 34 stations around SM: S1_SM - S32_SM (Fig. 1b); and 8 stations around NZ: S1_NZ - S8_NZ (Fig. 1b). A total of 67 sampling points from the 64 stations were covered, with an additional 3 samplings conducted at one of the stations at SM. Sampling was carried out during the month of April 2018 for coastal areas around MRU and ROD and during May 2018 for SM and NZ during the EAF-Nansen Indian Ocean Research Expedition 2018 on board the R/V Dr Fridtjof Nansen. The bathymetry map (Fig. 1b) gives an overview of the depth in the studied areas around the islands, where sampling was mostly done at depths less than 100 m, and at the banks where some stations were at depths greater than 400 m.

In-situ Chl*a* concentration analysis

Five hundred ml of surface seawater was collected in triplicate from each station to determine the *in-situ* Chl*a* concentration. Water samples were filtered using Whatman glass fiber filters of 0.45 µm pore size. Acetone (90% conc.) was used to extract the Chl*a* molecule from the filtrates. After 24 hrs, the extract was analyzed under a spectrophotometer at four different wavelengths (630, 647, 664 and 750 nm) (Sadally *et al*., 2014a). The Chl*a* concentration was determined based on the formula:

$$\text{Chlorophyll } a = (11.85^{*} (E_{664} - E_{750}) - 1.54^{*} (E_{647} - E_{750}) - 0.08 (E_{630} - E_{750})) {}^{*}V_e/L^{*}V_f$$

Where: L = Cuvette light-path in centimeters; V_e = Extraction volume in milliliters; V_f = Filtered volume in liters; and concentrations in mgm^{-3} (Jeffrey and Humphrey, 1975) based on revised extinction coefficients of chlorophylls *a, b, c1* and *c2*. These equations may be used for determining chlorophylls *a* and *b* in higher plants and green algae, chlorophylls a and *c1* + *c2* in brown algae, diatoms and chrysomonads, chlorophylls a and *c2* in dinoflagellates and cryptomonads, and chlorophylls *a*, *b*, and *c1* + *c2* in natural phytoplankton.

Satellite Chl*a* concentration analysis

Satellite data for Chl*a* concentration was extracted from the AquaMODIS (Moderate Resolution Imaging Spectroradiometer) level 3, version MODISA_v2018.0, with 4 km spatial resolution from the "NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group, 2018". These level 3 images contain data of geophysical variables that have been derived and mapped onto a specific spatial grid for a well-defined lapse of time and atmospherically corrected. Satellite Chl*a* and temperature map data were extracted and processed on GIOVANNI Version 4.35 (https://giovanni.gsfc.nasa.gov/giovanni/). For oligotrophic waters such as those found in most regions of the Indian Ocean, the algorithm CI was used which is based on three-band reflectance (red, blue and green) using the formula of Hu *et al*. (2012):

The images were then processed using the software SeaDAS version 7.3.1 (Lacava *et al*., 2018; Pinkerton, 2003). For each specific site, five standard pixels in line with the *in-situ* area, encompassing the Chl*a*, were chosen at a resolution of 4 km each and the average calculated (Guḥmundsson *et al*., 2009). Black pixels were eliminated from the average as these were due to natural atmospheric disturbances such as cloud coverage (Carswell *et al*., 2017).

Micro-phytoplankton sample collection and processing

Ten litres of sea surface water was collected and filtered through a 5 µm plankton net and the residue was preserved using 1% Lugol's solution and stored at 4°C (Sadally *et al*., 2014a; Soondur *et al*., 2020; Zarauz and Irigoien, 2008) while keeping the maximum time lapse between sampling and fixation below 15 minutes. Centrifugation was done at 3500 rpm for 10 minutes to concentrate the sample into a 1 ml pellet (Sadally *et al*., 2014a). The samples were kept at 4°C until further processing (Mukherjee *et al*., 2014). Identification of micro-phytoplankton was done according to Tomas (1996) and Smith and Johnson (1996), and quantification was performed by loading the 1ml phytoplankton concentrate onto a Sedgwick Rafter counting chamber under a light microscope (Woelkerling *et al*.,

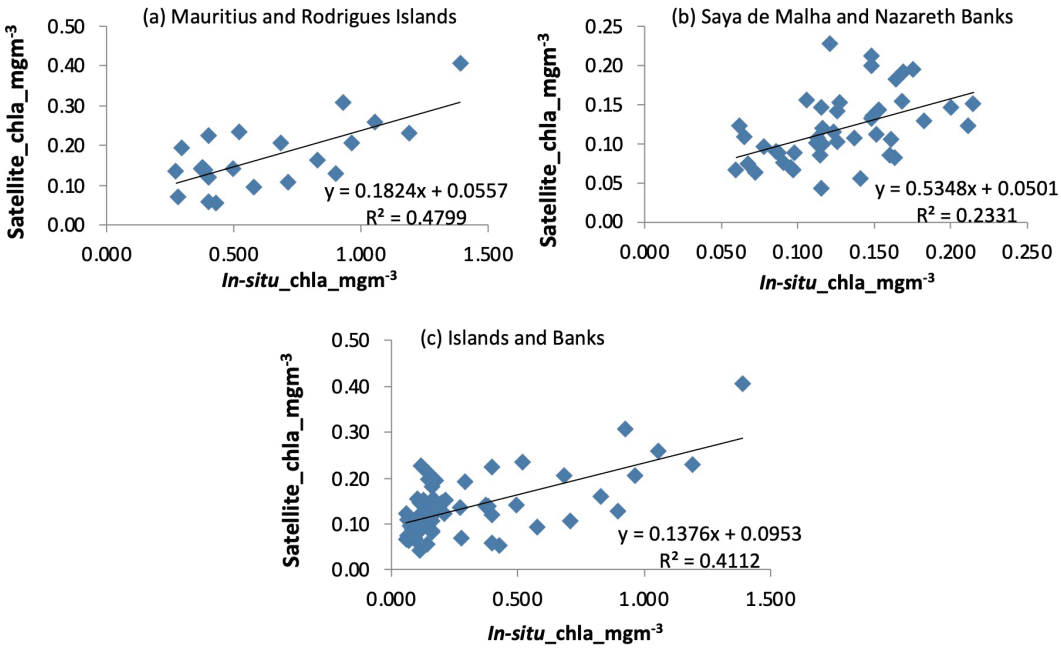

Figure 2. Scatter plot of average AquaMODIS satellite (average of 5 pixels for each data point) versus *in-situ* chlorophyll *a* (Chl*a*) data (3 replicates per data point). (a) Mauritius and Rodrigues Islands with 22 pairwise comparisons; (b) Saya de Malha and Nazareth Banks with 45 pairwise comparisons; and (c) Islands and Banks pooled to 67 pairwise comparisons.

1976; Devassy and Goes, 1991; Sadally *et al.*, 2014a). The counting of micro-phytoplankton was conducted at magnifications x100, x200 and x400 and classified into three groups of diatoms, dinoflagellates, and cyanobacteria for the islands, and only two groups of diatoms and dinoflagellates at the banks. The groups were further classified into different genera. The density of micro-phytoplankton was calculated as cells L^{-1} whereby the total micro-phytoplankton density (TMPD) was taken as the sum of the different groups of micro-phytoplankton.

Data processing and statistics

The software PASW Statistics 18 was used to analyze the data. Data was first checked for normality. Non-normally distributed data was transformed via log10 or Arcsine, and one-way ANOVA, Pearson's Correlation and Tukey's HSD Post-Hoc tests were performed. Statistical tests were considered significant at $\alpha = 5\%$ level. Shannon-Wiener (*H'*) and Evenness (E_{var}) diversity indices were used to determine the variability of the different micro-phytoplankton genera. Principal Component Analysis (PCA) was conducted to determine the correlation coefficient for the different regions and the biological parameters such as Chl*a* concentration for satellite and *in-situ*, TMPD, diatom, dinoflagellate and cyanobacteria densities. The software SeaDAS version 7.3.1 was used to process the satellite data.

Results

Validation/trend in Chl*a* variation for *in-situ* and remotely-sensed data

The Chl*a* concentration variation among the 67 sampling points indicated an underestimation in the

Table 1. The regions studied with the respective number of comparisons made between *in-situ* chlorophyll *a* and satellite chlorophyll *a*, R^2 values, Pearson correlation, and the significance level.

Regions	No. of comparisons (satellite chl*a* vs In-situ class)	R^2 values	Pearson correlation, (r values)	Significance
Mauritius and Rodrigues Islands	22	0.480	0.694	*P < 0.01*
Saya de Malha and Nazareth Banks	45	0.233	0.483	*P < 0.01*
Islands and Banks	67	0.411	0.642	*P < 0.01*

satellite Chl*a* data as compared to the *in-situ* Chl*a* data (Fig. 2). A total of 22 pairwise comparison sets of data were used for the islands and 45 for the banks. The islands gave rise to a R^2 of 0.480 and a correlation of 0.694, while the banks had an R^2 of 0.233 and a correlation of 0.483. Both correlation values were significant at ($P < 0.01$). Combining both islands and banks, 67 comparisons with an R^2 of 0.411 and a correlation of 0.642 resulted (Table 1).

Additional data was extracted from GIOVANNI (https://giovanni.gsfc.nasa.gov/giovanni/) and the variations of AquaMODIS satellite sea surface Chl*a* and temperature were determined. The data on Chl*a* concentration in the WIO showed similar trends during the average months of March-April and May-June 2018. During April, SST around the islands was greater than 27.0°C (Fig. 3a) and during May, the temperature dropped below 27.0°C (Fig. 3b). The same scenario was apparent at the banks where in April SST was greater than 28.5°C (Fig. 3c) and during May, it dropped below 28.5°C (Fig. 3d). On average there was a difference of 1.5°C between the islands and the banks.

Micro-phytoplankton density variation Mauritius and Rodrigues Islands

At MRU, the one-way ANOVA revealed a strong spatial difference among the 18 stations (S1_MUR - S18_MUR) for the total micro-phytoplankton density (TMPD), as well as for the diatom, dinoflagellates and cyanobacteria densities ($P < 0.001$) (Table 2). Highest TMPD were recorded in the eastern regions at stations S14_MRU ($19.4 \pm 1.4 \times 10^4$ cells L^{-1}), S15_MRU ($19.8 \pm 0.6 \times 10^4$ cells L^{-1}) and S16_MRU ($20.0 \pm 1.4 \times 10^4$ cells L^{-1}), and the lowest densities were mainly in the western region at S5_MRU ($8.6 \pm 0.8 \times 10^4$cellsL^{-1}), S6_MRU ($9.4 \pm 1.3 \times 10^4$ cells L^{-1}) and S12_MRU ($7.7 \pm 0.8 \times 10^4$ cells L^{-1}) (Fig. 4). Diatoms contributed most to the TMPD followed by dinoflagellates and cyanobacteria. The highest and lowest densities of diatoms was recorded at the same

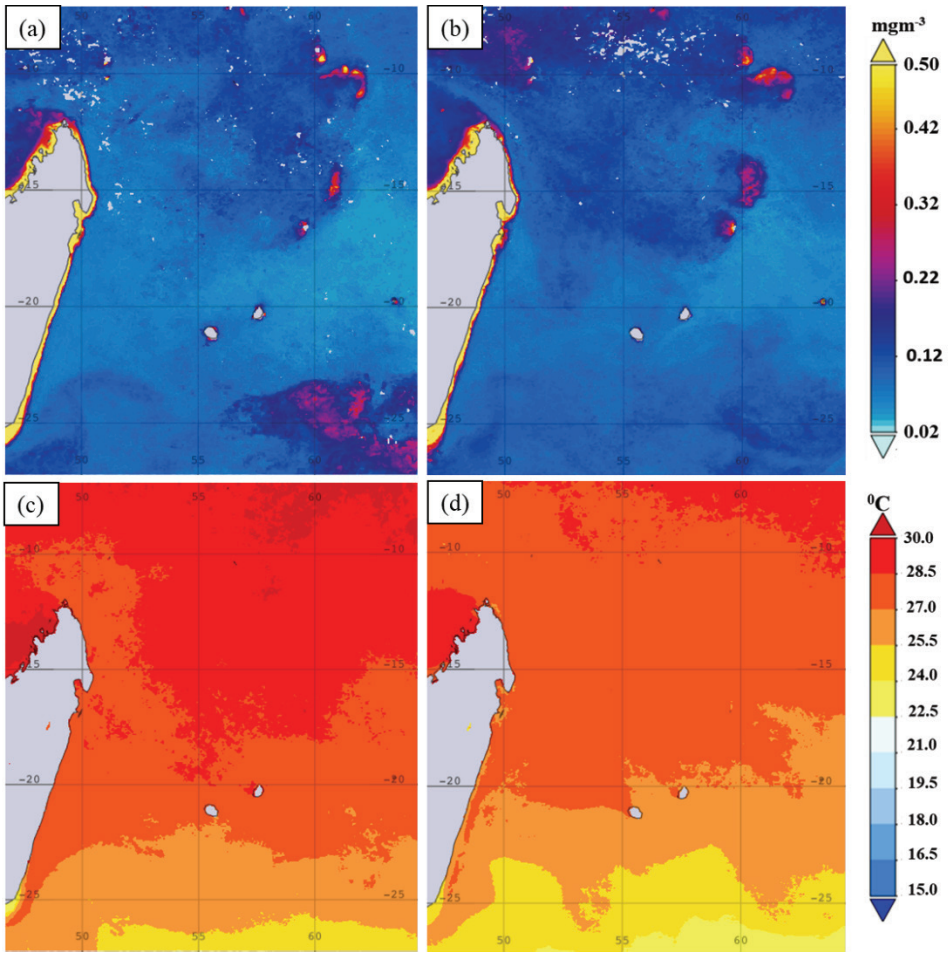

Figure 3. Average AquaMODIS satellite data: (a) Sea Surface Chl*a* concentration for April 2018; (b) Sea Surface Chl*a* concentration for May 2018; (c) Sea Surface Temperature for April 2018; and (d) Sea Surface Temperature for May 2018.

Table 2. One-way ANOVA for comparing the different densities of total micro-phytoplankton, diatom, dinoflagellates and cyanobacteria at different stations at the islands and banks.

Islands	**Mauritius**					**Rodrigues**				
Total micro-phytoplankton	SS	df	MS	F	P-value	SS	df	MS	F	P-value
Between Stations	12.136	19	0.639	49.949	***	2.215	3	0.738	99.115	***
Diatom										
Between Stations	3.439	19	0.181	25.711	***	0.626	3	0.209	24.889	***
Dinoflagellates										
Between Stations	1.125	19	0.059	18.108	***	0.253	3	0.084	37.679	***
Cyanobacteria										
Between Stations	0.416	19	0.022	10.658	***	0.055	3	0.018	15.803	***
Banks	**Saya de Malha**					**Nazareth**				
Total Phytoplankton	SS	df	MS	F	P-value	SS	df	MS	F	P-value
Between Stations	0.577	36	0.016	11.627	***	0.047	7	0.007	8.324	***
Diatom										
Between Stations	0.294	36	0.008	10.468	***	0.038	7	0.005	8.932	***
Dinoflagellates										
Between Stations	0.088	36	0.002	4.323	***	0.002	7	0.000	0.580	*NS*

*P < 0.001 = ***, P < 0.01 = **, P < 0.05= *, NS = Not Significant*

stations as the total micro-phytoplankton, and ranged between 4.0 ± 0.6 ×10⁴ cells L⁻¹ and 10.4 ± 1.0 ×10⁴ cells L⁻¹ (Fig. 4). Moreover, S14_MRU also recorded the highest density of dinoflagellates of 6.7 ± 0.9 ×10⁴ cells L⁻¹. S12_MRU, which recorded the lowest diatom density, also recorded the lowest density of dinoflagellates (2.7 ± 0.5 ×10⁴ cells L⁻¹) and cyanobacteria (1.0 ± 0.2 ×10⁴ cells L⁻¹), while S16_MRU had the highest density of cyanobacteria (3.4 ± 1.1 ×10⁴ cells L⁻¹) (Fig. 4). Out of the 18 stations around MRU, stations that recorded ≥ 50% dominance in diatoms were S1_MRU, S2_MRU, S3_MRU, S4_MRU, S7_MRU, S8_MRU, S9_MRU, S10_MRU, S11_MRU, S12_MRU, S15_MRU, S16_MRU, S17_MRU (Fig. 5).

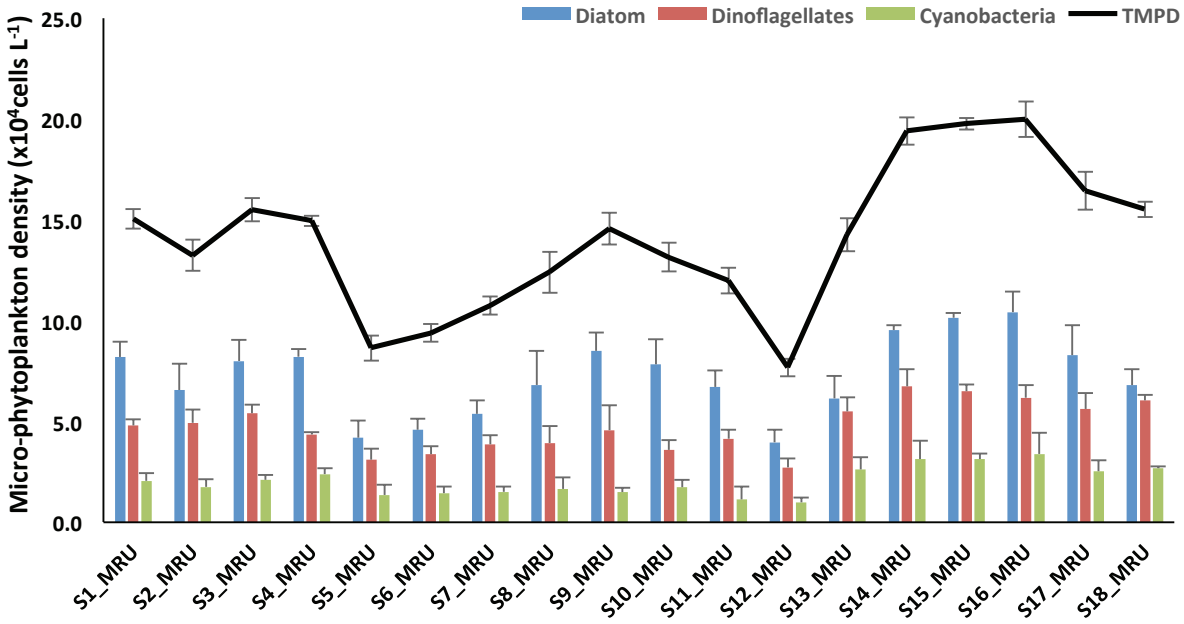

Figure 4. Densities of total micro-phytoplankton (TMPD), diatom, dinoflagellates and cyanobacteria around Mauritius Island (MRU) at 18 stations, where station is referred to as "S".

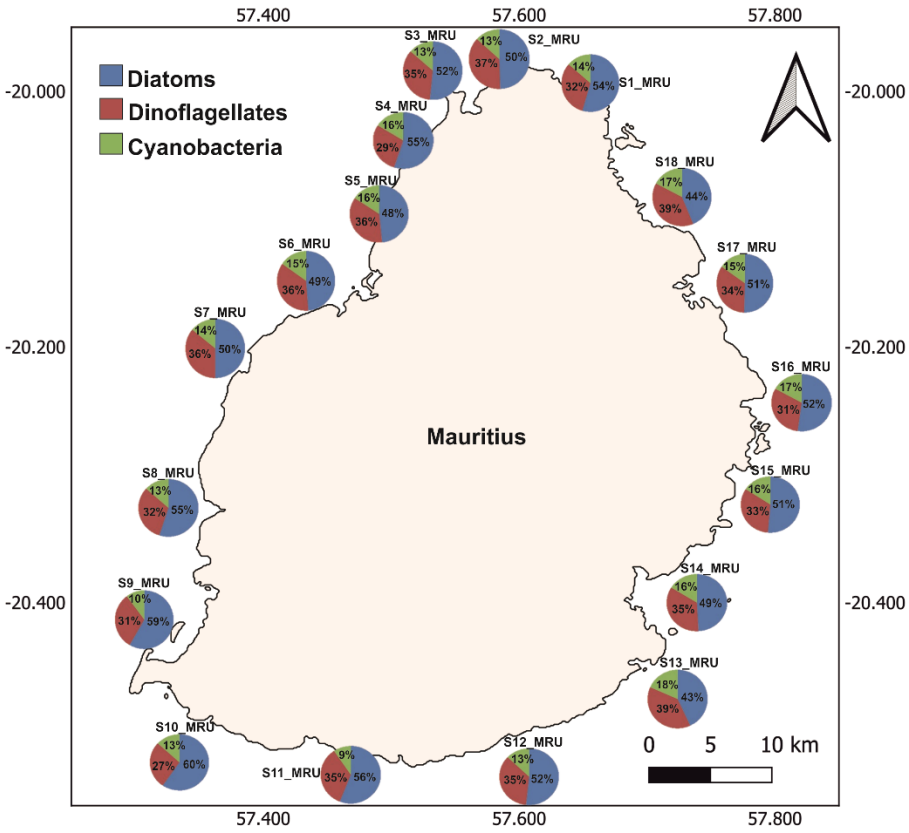

Figure 5. Percentage composition of the three groups of micro-phytoplankton (diatom, dinoflagellates and cyanobacteria) around Mauritius Island (MRU) where station is referred to as "S".

At ROD, the densities mainly followed the trend S1_ROD > S2_ROD > S4_ROD > S3_ROD. This trend was the same for the total micro-phytoplankton, diatom and dinoflagellates densities, except for the cyanobacteria where the lowest density was recorded at station S4_ROD. The total micro-phytoplankton ranged between 17.6 ± 1.2 × 10^4 cells L^{-1} and 8.8 ± 0.2 × 10^4 cells L^{-1}; diatoms between 9.1 ± 1.4 × 10^4 cells L^{-1} and 4.6 ± 0.5 × 10^4 cells L^{-1}; dinoflagellates between 6.0 ± 0.3 × 10^4 cells L^{-1} and 2.7 ± 0.5 ×10^4 cells L^{-1}; and cyanobacteria between 2.5 ± 0.3 × 10^4 cells L^{-1} and 1.5 ± 0.3 × 10^4 cells L^{-1} (Fig. 6). At the 4 stations around ROD, all recorded

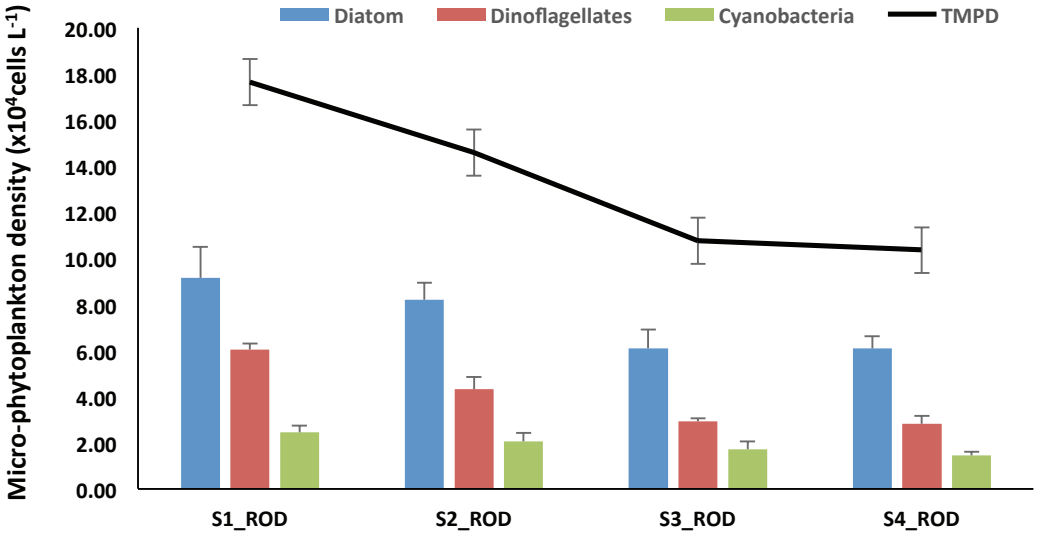

Figure 6. Densities of total micro-phytoplankton (TMPD), diatom, dinoflagellates and cyanobacteria around Rodrigues Island (ROD) at 4 stations, where station is referred to as "S".

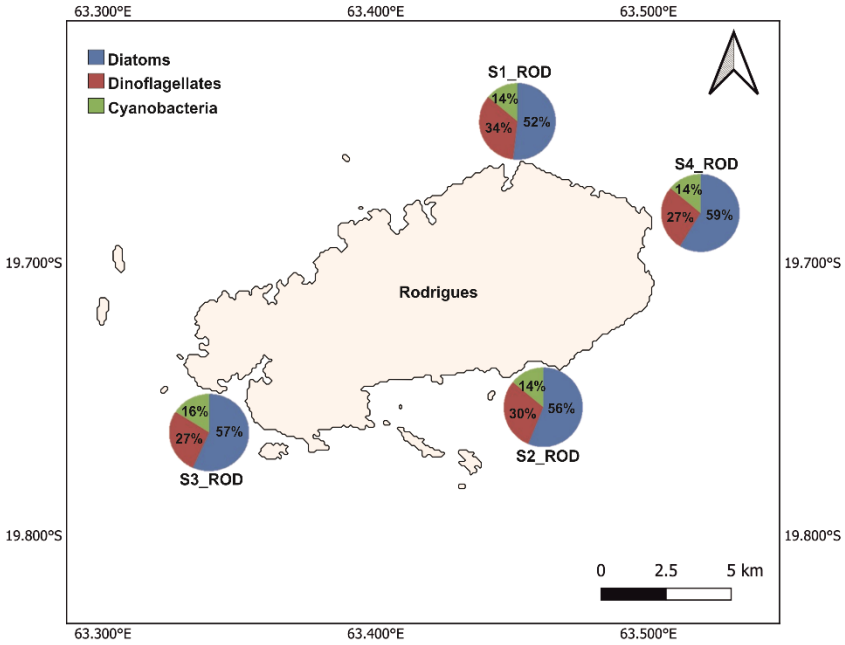

Figure 7. Percentage composition of the three groups of micro-phytoplankton (diatom, dinoflagellates and cyanobacteria) around Rodrigues Island (ROD) where station is referred to as "S".

≥ 50% dominance in diatoms (Fig. 7). Site-wise, for the different densities (total micro-phytoplankton, diatom, dinoflagellates and cyanobacteria), the one-way ANOVA test confirmed that there were strong significant differences at ($P < 0.001$) (Table 2).

Saya de Malha and Nazareth Banks

At SM the total micro-phytoplankton densities ranged between 3.0 - 4.0 x 10^4 cells L^{-1} for most stations except for S5_SM, S7_SM, S12_SM, S16_SM and S20_SM which had higher than 4.0 x 10^4 cells L^{-1} (Fig. 8). The highest diatom densities were recorded at station S5_SM, S7_SM, S12_SM and S16_SM which was above 3.0 x 10^4 cells L^{-1} (Fig. 8). For the rest of the stations, the densities were below 3.0 x 10^4 cells L^{-1}. The densities of dinoflagellates varied highly with the highest density recorded at station S12_SM (1.9 x 10^4 cells L^{-1}) and the lowest at S22_SM (0.8 x 10^4 cells L^{-1}) (Fig. 8). All the

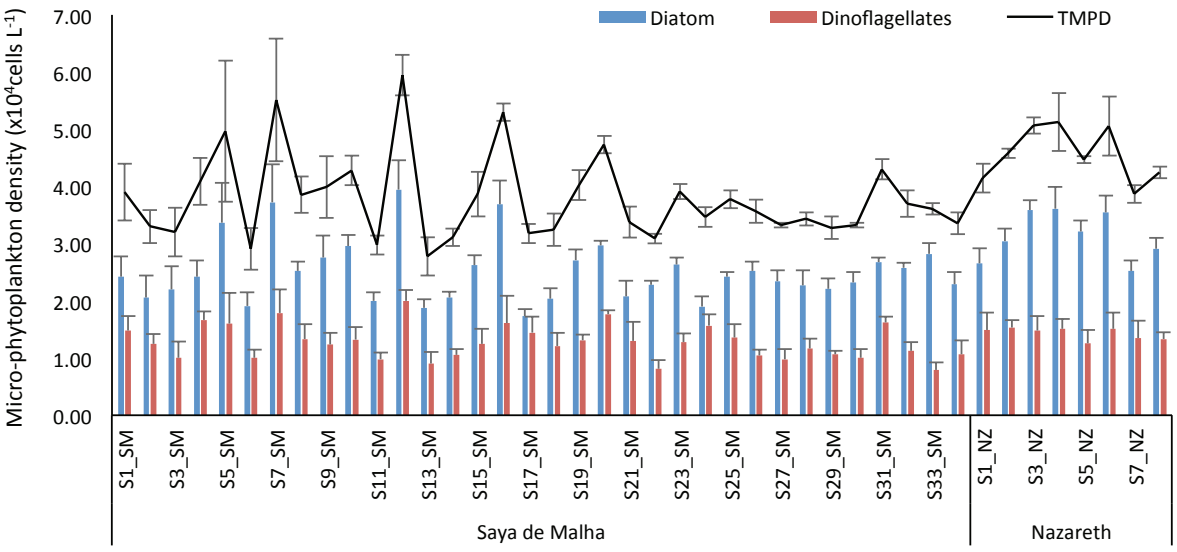

Figure 8. Densities of total micro-phytoplankton (TMPD), diatom and dinoflagellates in the Mascarene region at Saya de Malha (SM) and Nazareth (NZ) Banks where station is referred to as "S".

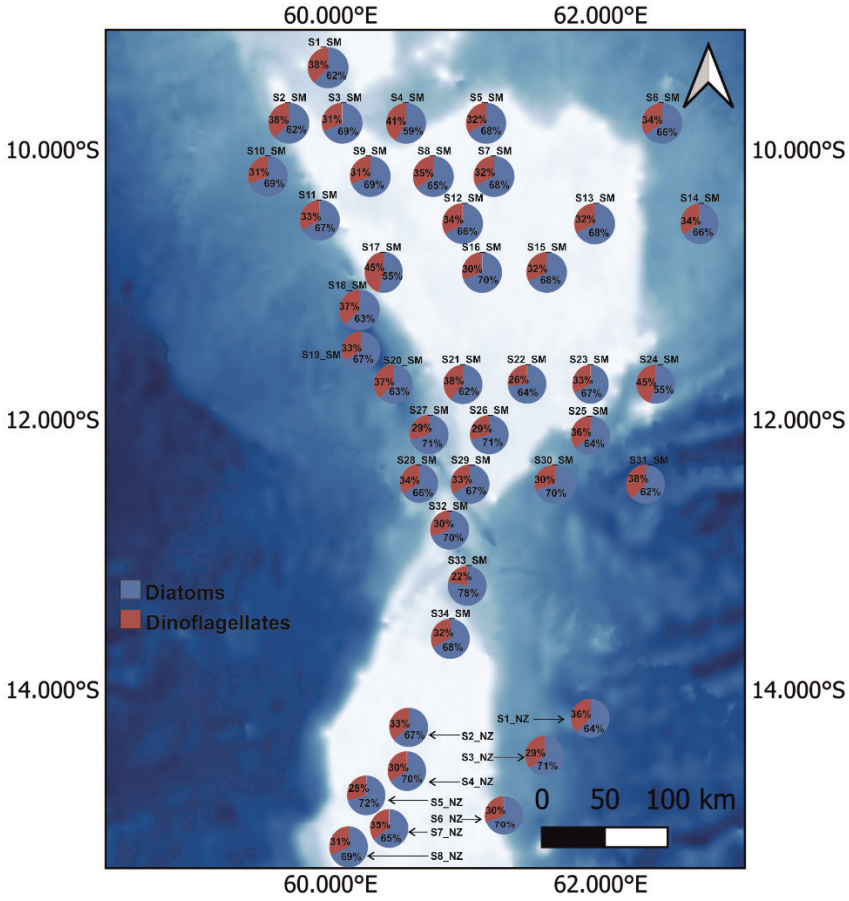

Figure 9. Percentage composition of the two groups of micro-phytoplankton (diatom and dinoflagellates) in the Mascarene region at Saya de Malha (SM) and Nazareth (NZ) Banks where station is referred to as "S".

34 stations recorded diatoms as the dominant group, and stations that showed diatom percentages ≥ 70% were S16_SM, S26_SM, S27_SM, S30_SM, S32_SM and S33_SM (Fig. 9). The one-way ANOVA showed the stations differed significantly ($P < 0.001$) for all the densities of total micro-phytoplankton, diatoms and dinoflagellates (Table 2).

At NZ, it was found that apart from station S6_NZ, all the other stations' total micro-phytoplankton densities were above 4.0 x 10^4 cells L^{-1}. The highest diatom densities were recorded at S2_NZ, S4_NZ and S6_NZ with over 1.5 x 10^4 cells L^{-1} and the lowest density was recorded at S7_NZ (1.2 x 10^4 cells L^{-1}) (Fig. 8). The densities of dinoflagellates at NZ did not differ a lot. Among the demarcations, the lowest density of dinoflagellates was recorded at station S5_NZ. The dominance of diatoms prevailed with diatom percentage ≥ 70% observed at S3_NZ, S4_NZ, S5_NZ, S6_NZ (Fig. 9). The one-way ANOVA showed the density of dinoflagellates between the stations did not differ significantly ($P > 0.05$) but for the total phytoplankton and diatom densities, the difference was significant at ($P < 0.001$) (Table 2).

Principal component analyses

The Principal Component Analysis (PCA) was performed with the data from the islands and banks separately. The parameters that were considered were the *in-situ* Chl*a*, satellite Chl*a*, and the densities of diatom, dinoflagellates, cyanobacteria, and total micro-phytoplankton. Around the islands, the PCA explained 85.50% of the total data variance where F1 had more influence with 72.33% (Eigen value = 4.340) compared to F2 with 13.47% (Eigen value = 0.790) (Fig. 10a). A similar trend was observed at the banks where F1 had more influence with 57.77% (Eigen value = 2.954) and F2 with 24.91% and a total of 82.68% (Eigen value = 1.219) (Fig. 10b). A high correlation between the satellite and *in-situ* Chl*a* concentration both at the islands and the banks was revealed (Fig 10). The PCA showed the highest correlation of TMPD with diatom and dinoflagellates followed by cyanobacteria for the islands. Compared to the islands, the banks had a

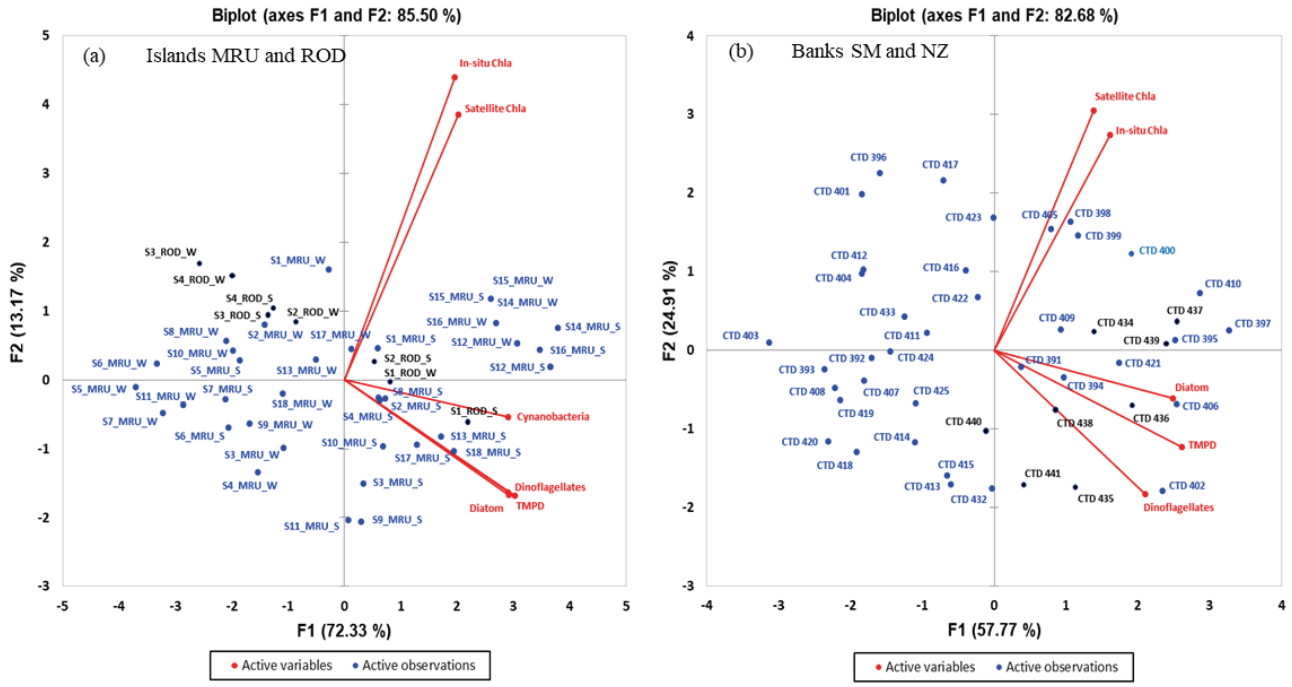

Figure 10. The Principal Component Analysis (PCA) representing correlation coefficient analysis for the different regions and the biological parameters of Chlorophyll *a* (Chl*a*) concentration for satellite and *in-situ*, Total Micro-Phytoplankton Density (TMPD), Diatom, Dinoflagellates and Cyanobacteria densities. (a) Mauritius Island (MRU) with 18 stations and Rodrigues Island (ROD) with 4 stations; and (b) Saya de Malha Bank (SM) with 32 stations and Nazareth Bank (NZ) with 8 stations.

higher positive correlation with the TMPD in diatoms compared to the dinoflagellates (Fig. 10).

Micro-phytoplankton diversity

The diversity of the micro-phytoplankton was investigated at 18 sites around MRU where 47 different genera were identified out of which 28 were diatoms, 12 dinoflagellates and 7 cyanobacteria. Around ROD (4 sites), 47 different genera of micro-phytoplankton were identified of which 28 were diatoms, 12 dinoflagellates and 7 cyanobacteria. On the Mascarene Plateau at the banks of SM and NZ, 23 diatoms and 11 dinoflagellates genera were identified. Figure 11 shows some of the common genera of micro-phytoplankton identified in the EEZ of the Republic of Mauritius.

On average at the four different sites the most dominant diatoms genera in terms of percentage in the community structure were *Coscinodiscus* (14.64%), *Navicula* (11.78%), *Nitzschia* (8.87%), *Chaetoceros* (8.27%), *Fragilaria* (5.68%) and *Licmorphora* (5.04%). *Coscinodiscus* and *Navicula* were the two diatom genera that were uniformly present at the four different sites. *Fragilaria* and *Licmorphora* were abundant around the islands (> 7.00%) compared to the banks (< 3.00%). For the dinoflagellates, *Ceratium* occupied the highest percentage accounting for 24.01%, followed by *Peridinium* (16.43%), *Oxyphysis* (13.09%), *Oxytoxum* (11.99%) and *Dinophysis* (8.24%). Out of the 5 dominant dinoflagellates genera, all showed consistency in percentage distribution. Cyanobacteria were identified only at the islands of MRU and ROD where the four most abundant genera were *Anabaena* (21.30%), *Lyngbya* (19.86%), *Nodularia* (19.30%) and *Oscillatoria* (17.77%). Some genera like *Actinoptuchus*, *Asteromphalus*, *Proboscia* and *Rhizosolenia* showed considerably higher densities at the banks compared to the islands (Table 3).

Shannon-Wiener and Evenness indices

The Shannon-Wiener diversity index revealed that the distribution of diatoms around MUR and ROD, and SM and NZ were all above H' > 2.5 with the islands having higher mean values compared to the banks. For the dinoflagellates, the H' was between 2 and 2.5 and for the cyanobacteria groups at MUR and ROD, the values ranged between 1.5 and 2 (Fig. 12a). The mean of the Evenness of dinoflagellates at SM was nearly the same as at NZ, but for the diatom, it was totally different. Overall, the different classes of micro-phytoplankton around the islands were more evenly distributed with a mean of the E_{var} > 0.6 compared to

Table 3. The percentage genera composition of different micro-phytoplankton at Mauritius (MRU), Rodrigues (ROD), Saya de Malha (SM) and Nazareth (NZ) Banks where the total percentage of each of micro-phytoplankton groups (diatom/dinoflagellates/cyanobacteria) made up 100%. Bold and highlighted cells indicate high percentages observed.

	Genera	MRU	ROD	SM	NZ	EEZ
Diatom	*Actinoptuchus*	1.70	2.26	4.93	3.94	3.21
	Asteromphalus	1.68	2.55	4.57	3.53	3.08
	Asterionellopsis	1.85	2.18	0.66	0.58	1.32
	Biddulphia	1.49	2.02	0.64	0.48	1.16
	Bleakeleya	1.87	1.81	0.00	0.00	1.84
	Chaetoceros	**7.40**	**5.96**	**9.94**	**9.77**	**8.27**
	Coscinodiscus	**14.27**	**11.81**	**15.95**	**16.55**	**14.64**
	Dactyliosolen	1.66	1.28	2.48	2.89	2.08
	Detonula	1.81	2.06	1.12	1.68	1.67
	Diploneis	2.03	1.69	0.00	0.00	1.86
	Eucampia	2.17	1.97	1.57	2.23	1.99
	Fragilaria	**7.71**	**11.93**	**1.92**	**1.17**	**5.68**
	Guinardia	2.27	2.18	1.17	1.17	1.70
	Haslea	1.71	2.06	0.00	0.00	1.88
	Hemiaulus	2.20	2.47	1.73	2.14	2.13
	Leptocylindrus	2.54	2.71	1.88	4.75	2.97
	Licmorphora	**7.55**	**8.14**	**1.47**	**2.98**	**5.04**
	Lioloma	2.06	1.60	0.00	0.00	1.83
	Melosira	1.74	1.11	1.36	1.08	1.32
	Odontella	1.88	2.02	0.00	0.00	1.95
	Proboscia	1.92	2.26	5.19	7.60	4.24
	Rhizosolenia	1.73	1.40	4.61	8.91	4.16
	Skeletonema	2.01	1.73	2.08	3.85	2.42
	Thalassiosira	2.11	2.34	0.32	0.93	1.43
	Navicula	**10.73**	**9.50**	**15.08**	**11.81**	**11.78**
	Nitzschia	**8.44**	**7.90**	**13.23**	**5.91**	**8.87**
	Pseudo_Nitzschia	3.16	2.71	3.45	3.49	3.20
	Thalassionema	2.29	2.34	4.63	2.56	2.96
Dinoflagellates	*Alexandrium*	2.72	3.24	2.37	2.38	2.68
	Amphidinium	5.26	5.94	3.46	4.63	4.82
	Ceratium	**24.89**	**22.48**	**23.73**	**24.92**	**24.01**
	Dinophysis	**7.88**	**7.36**	**8.28**	**9.42**	**8.24**
	Gonyaulax	3.98	5.06	5.17	6.02	5.06
	Gymnodinium	2.58	3.92	3.66	5.02	3.80
	Oxyphysis	**10.45**	**10.53**	**16.59**	**14.79**	**13.09**
	Oxytoxum	**10.67**	**10.47**	**12.76**	**14.08**	**11.99**
	Peridinium	**19.71**	**19.24**	**14.63**	**12.15**	**16.43**
	Polykriskos	3.47	3.78	5.40	3.44	4.02
	Prorocentrum	3.53	3.78	0.00	0.00	3.65
	Pyrocystis	4.86	4.19	3.94	3.15	4.03
Cyanobacteria	*Anabaena*	**23.07**	**19.54**	0.00	0.00	**21.30**
	Lyngbya	**19.10**	**20.62**	0.00	0.00	**19.86**
	Nodularia	**19.60**	**19.00**	0.00	0.00	**19.30**
	Oscillatoria	**17.23**	**18.32**	0.00	0.00	**17.77**
	Phormidium	10.58	7.73	0.00	0.00	9.16
	Snowella	5.43	8.55	0.00	0.00	6.99
	Spirulina	5.01	6.24	0.00	0.00	5.62

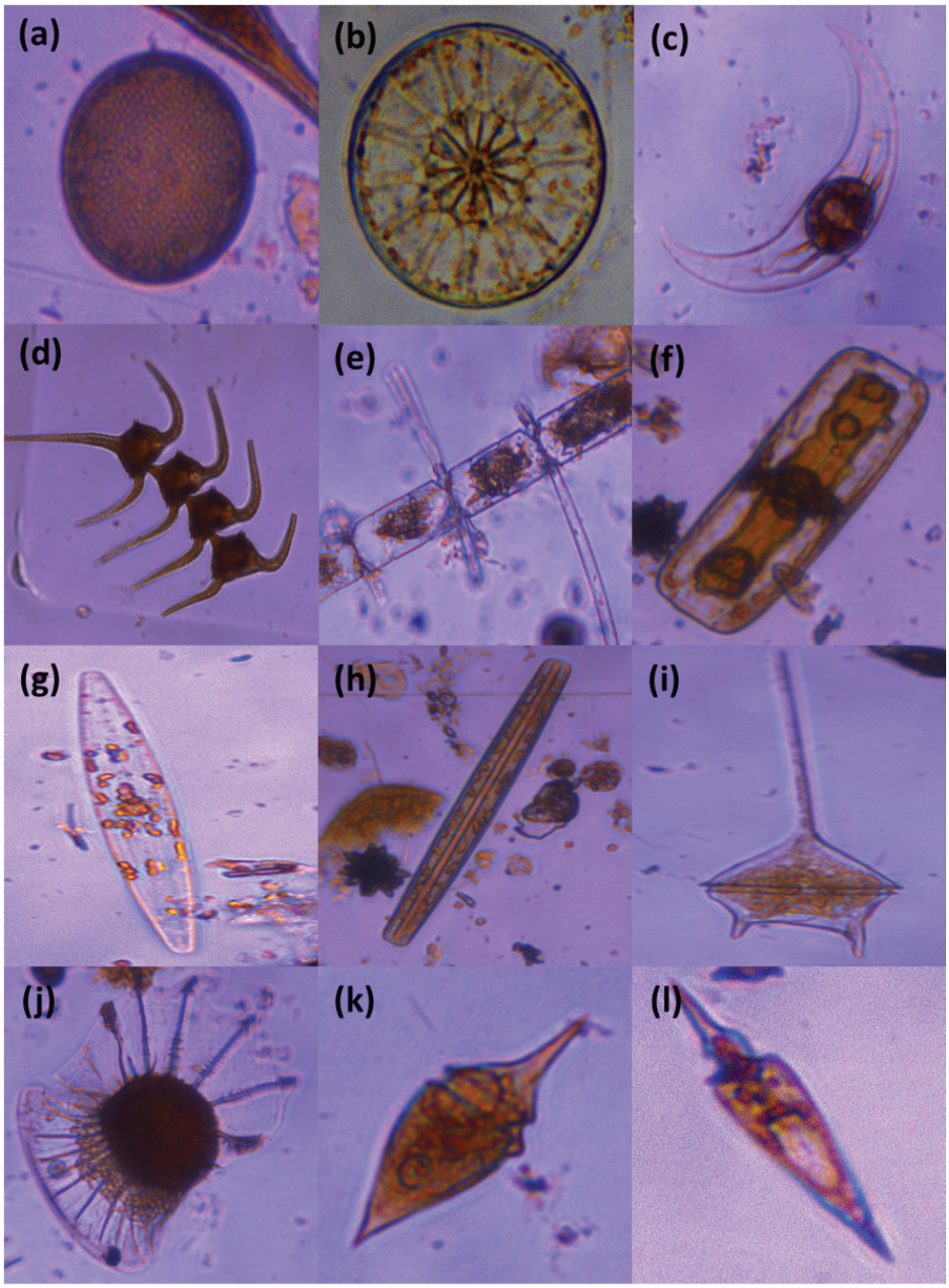

Figure 11. Common micro-phytoplankton genera in the EEZ of the Republic of Mauritius and the Joint Management Area (JMA) between the Republic of Mauritius and Republic of Seychelles. a) *Coscinodiscus*; b) *Asteromphalus*; c) *Pyrocystis*; d) *Ceratium sp1*; e) *Chaetoceros*; f) *Navicula*; g) *Nitzschia*; h) *Thalassionema*; i) *Ceratium sp2*; j) *Dinophysis*; k*) Oxyphysis*; l) *Oxytoxum.*

the fishing banks with a mean E_{var} < 0.6, except for the group of cyanobacteria around ROD which had a mean of E_{var} < 0.6 (Fig. 12b). Overall, the diatom had higher genera variability followed by dinoflagellates and cyanobacteria. The Shannon-Wiener indices revealed that the highest biodiversity was among the genera of diatoms. A high Evenness value showed that the number of individual genera of micro-phytoplankton was fairly equal.

Discussion

Oligotrophic waters are categorized as being exceptionally clear due to very low concentrations of chlorophyll and low levels of chromophoric dissolved organic matter. Furthermore, these waters have low concentration of nutrients and phytoplankton biomass which depict low primary productivity (Jena *et al*., 2013). In this study, satellite data indicated low concentrations of Chl*a* in the Indian Ocean waters

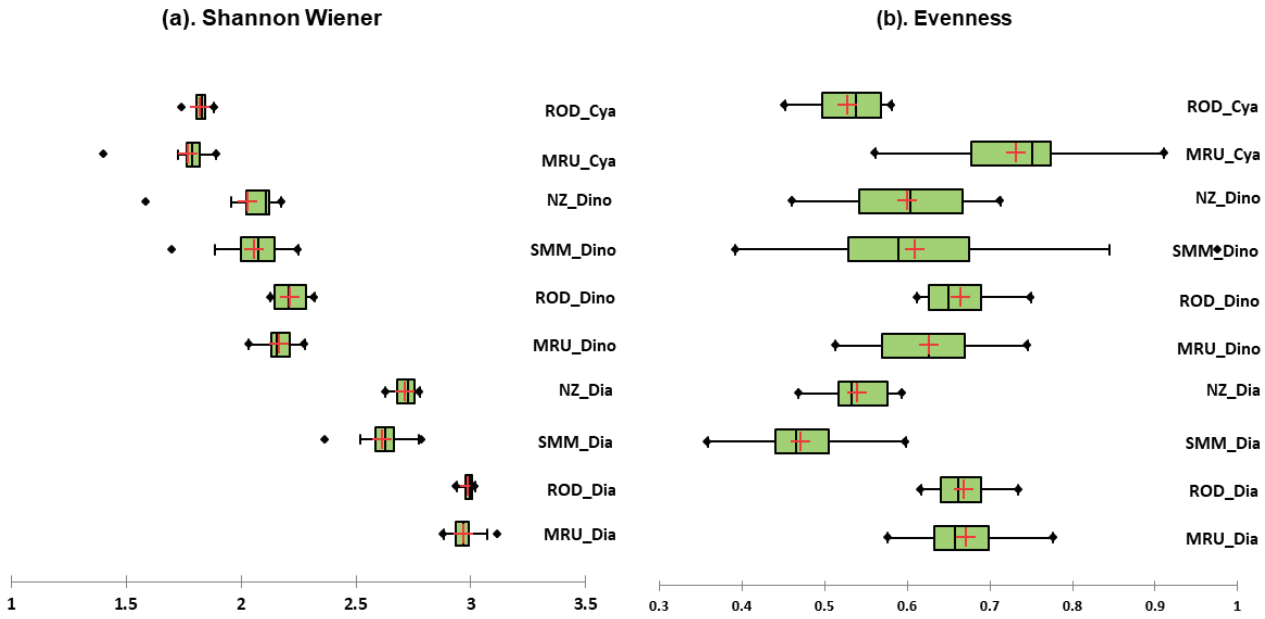

Figure 12. The representation of box plots for the diversity indices of the biological parameters Diatom (Dia), Dinoflagellates (Dino), and Cyanobacteria (Cya) at the islands of Mauritius (MRU) and Rodrigues (ROD) and the banks of Saya de Malha (SM) and Nazareth (NZ) where (a) is the Shannon Wiener (H') and (b) is Evenness (E_{var}).

around the islands of MRU and ROD, and the Mascarene Plateau. This observation corroborated studies that reported the Southern Indian Ocean as having oligotrophic waters (Morel *et al*., 2010). Using the algorithm developed by Hu *et al*. (2012), the AquaMODIS Chl*a* satellite was effectively used in oligotrophic waters where the concentration of Chl*a* is ≤ 0.25 mg m^{-3}. Several studies worldwide have supported the use of satellite data (Gregg and Rousseaux, 2014; Mudgal *et al*., 2009; Tilstone *et al*., 2013).

Several studies have investigated the relationship between satellite and *in-situ* Chl*a* data and the strength of R^2 values were found to be variable. A study conducted by Gregg and Casey (2004) reported a fairly low R^2 value for the regression between satellite and *in-situ* Chl*a* concentration data in regions near the Equatorial Indian Ocean, whereas the southern Indian Ocean had a higher value. Low R^2 values (0.168 and 0.116) for satellite verses *in-situ* Chl*a* data were found in Maltese coastal waters (Deidun *et al*., 2011) but requires ground truthing against in situ measurements. The aim of this study is to attempt the statistical comparison of MODIS ocean colour data, for a near-shore marine area off the north-east coastline of Malta, with in situ surface chlorophyll-a measurements, and to extract a twelve-month ocean colour data series for the same marine area. Peaks in surface chlorophyll-a concentration occurred in the January-February period, with lowest values being recorded during the early spring period. Log bias values indicate that the MODIS dataset under-estimates the surface chlorophyll-*a* values, whilst RMSD and R^2 values suggest that the match-up between satellite and in situ values is only partly consistent. and it was attributed to the low set of matchup comparisons. In the present study lower R^2 values were recorded at SM and NZ (nearer the Equatorial Indian Ocean) compared to those around MRU and ROD Islands (in the southern Indian Ocean). It is noteworthy that even with a relatively low number of pairwise comparison data sets (67) obtained during April and May 2018, there was a significant correlation (R^2 of 0.411; 0.642; $P < 0.01$) between satellite and *in-situ* Chl*a* concentration, explaining about half of the variance in the *in-situ* values. This suggests that satellite Chl*a* data from the AquaMODIS sensor may act as a relatively good potential predictor of spatial trends in the EEZ of the Republic of Mauritius and in the JMA. A larger number of comparative data points for the satellite and *in-situ* Chl*a* would probably minimize the scatter in the relationship and the margin of bias and error (Clerici *et al*., 2008; Fleming and Korb, 2004). Additional data points at different times of the season and for several years would generate a more robust dataset for appropriate assessments of seasonal and inter-annual variations, and may increase the confidence of this validation and yield a higher R^2 value.

The inhabited Islands of MRU and ROD are expected to be affected by anthropogenic activities as compared

to the remote regions of the Mascarene Plateau like SM and NZ (Ramessur, 2002). Thus, the higher density of micro-phytoplankton recorded around both islands compared to the two banks may be attributed to the Island Mass Effect (IME) being higher at the islands, linked to anthropogenic influences, compared to the remote Mascarene regions. Elliott *et al*. (2012) and eddies on the downstream side of the island that form in both tidal and steady currents. In some cases, runoff from the island and/or exchange with a lagoonal system can enhance nearshore production. Phytoplankon blooms in otherwise oligotrophic systems have the potential to increase nearshore zooplankton abundance. Greater availability of nearshore zooplankton may help reefs cope with stressors such as bleaching events. Palardy *et al.* (2008) used remote sensing to confirm an IME around MRU and ROD. The IME tends to boost primary productivity more around oceanic islands compared to the adjacent waters. Several physical factors drive the IME including tidal change, runoff of freshwater with its associated nutrient loading, coastal upwelling due to wind velocity coupled with mass water flow, wave actions, and Ekman transport (Jena, 2016). Tidal changes that occur four times in a diel cycle promote the mixing of the different water layers which may enhance primary productivity and an increase in phytoplankton biomass (Blauw *et al*., 2012) we analyzed fluctuations in coastal phytoplankton concentration in relation to the tidal cycle. Time series of chlorophyll fluorescence, suspended particulate matter (SPM).

Around MRU, higher total micro-phytoplankton density was recorded in the south-east region, and the lowest in the extreme south region. The south-east region of Mauritius is characterized by many river discharges and highly turbid waters (Turner and Klaus, 2005) having high organic matter content which is converted to nutrients by bacterial recycling and enhances phytoplankton growth. Furthermore, there are mangrove areas in these specific regions (Appadoo, 2003) which promote the growth of phytoplankton (Saifullah *et al*., 2016). The southern region of MRU is characterized by high wave action and there is an absence of high reef barriers on certain parts of the coast (Elliott *et al*., 2018; Turner and Klaus, 2005). This potentially leads to a higher mixing rate of the water which in turn leads to a decrease in the phytoplankton density.

Sadally *et al*. (2014a) reported a low density of phytoplankton at certain sites around MRU, especially around the reef zone where there is high levels of water flushing. Furthermore, the southeast trade winds probably enhance coastal upwelling and give a boost to primary productivity in the eastern region of MRU (González-Rodríguez *et al*., 2012) a highly productive area off the western coast of the Baja California Peninsula, is examined for five successive years (2003-2007). In the northern and southern parts of ROD, the presence of mangrove ecosystems explains the higher density of micro-phytoplankton compared to the eastern and western zones. ROD most probably faces the impacts of anthropogenic activities as does MRU together with the input of nutrients from runoff to promote the growth of phytoplankton. The rate of runoff at ROD may be greater as it is a more mountainous island.

The plankton dynamics around the Mascarene Plateau is mainly influenced by natural environmental drivers such as wave action, upwelling, mass water flow, and climate change. This region may be least affected by direct anthropogenic activities owing to its distant location from the inhabited islands of MRU and ROD, and subsequent inaccessibility. Badal (2003) highlighted that a mini-monsoon had enhanced the primary productivity on the Mascarene Plateau. The high productivity in the region of the Mascarene Plateau can be attributed to the shallowness of the fishing banks of SM and NZ that may cause accumulation of nutrients rising to the upper layer of the water through upwelling (Vortsepneva, 2008). Lower phytoplankton density on the Mascarene Plateau may be attributed to the open ocean circulation that may impact both density and diversity.

This study revealed that the islands of MRU and ROD, and the SM and NZ of the Mascarene region had higher diatom density compared to dinoflagellates. This trend has been observed in several studies (Aubry *et al*., 2006; Devassy and Goes, 1991; Sadally *et al*., 2014). Diatoms are known to be more robust and adaptive to changes in environmental conditions such as temperature and salinity. The reproductive rate of diatoms is very high (Chepurnov *et al*., 2004). The dominant species in this study, *Navicula* and *Coscinodiscus,* were also reported to be abundant in many other studies. *Fragilaria* was most abundant at sites near freshwater rivers. The genera *Fragilaria* has been reported to be highly abundant in some freshwater ecosystems (Almeida *et al*., 2016).

Conclusion

Satellite-derived sea surface Chl*a* concentrations in the Mascarene Plateau region and the EEZ of Mauritius may be used as a good proxy for *in-situ* Chl*a*, with a fair level of confidence. These data may potentially serve as a basis to better determine areas of high productivity and eventually contribute towards achieving sustainability in the fisheries sector. Variable micro-phytoplankton density and diversity was found at the studied stations and regions. Densities were higher around the islands compared to the open sea on the Mascarene Plateau, though the micro-phytoplankton communities tended to be dominated by similar genera. It is important to explore the existing limited data set so that future studies may advance this field of study through further data collection and analyses, especially in the data-deficient Mascarene region. Further research is warranted in order to thoroughly capture the intra- and inter-annual variations in Chl*a* and micro-phytoplankton distribution on the Mascarene Plateau.

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