Inorganic nutrient distribution at Saya de Malha and the eastern slope of the Nazareth Banks

Anishta Audit-Manna*, Reeya K. Oogarah, Yashvin Neehaul

Mauritius Oceanography Institute, Avenue des Anchois, Morcellement de Chazal, Albion 91005, Mauritius

* Corresponding author: aauditmanna@moi.intnet.mu

Abstract

The distribution of nutrients in the Mascarene Plateau is poorly studied due to limited data collected in the region. This study investigated the distribution of nutrients in the water column of the Saya de Malha and eastern slope of the Nazareth Banks. Water samples were collected at the Saya de Malha and eastern slope of Nazareth Banks during the scientific expedition on board the R/V Fridtjof Nansen in May 2018 and the vertical profiles of physical parameters were used to identify the different water masses. Phosphate, nitrate and silicate showed typical nutrient profiles along with the nutriclines. The dissolved oxygen and chlorophyll-*a* showed a correlation with nutrients. Most of the sampling stations on the Saya de Malha and Nazareth Banks showed high oxygen saturation above 92 % in the upper 75 m. Low chlorophyll-*a* values were recorded at both banks indicating an oligotrophic system. The nutrient results also reveal an increase in the concentration towards the northern part of the region due to the South Equatorial Current crossing the plateau.

Keywords: nutrients, Saya de Malha Bank, Nazareth Bank, South Equatorial Current, Western Indian Ocean, primary productivity

Introduction

The physical oceanography of the Southern Indian Ocean (SIO) remains poorly studied compared to the northern parts of the Indian Ocean or other ocean basins such as the South Atlantic (New *et al.,* 2005). This is due to limited research surveys carried out in the SIO region, resulting in less hydrographic data being available (Badal *et al.,* 2009; Stramma and Lutjeharms, 1997). The research surveys conducted have mainly been based on the currents, water masses or chlorophyll concentrations. Following the hydrographic survey of the RSS Charles Darwin in 2002, the presence of large-scale flow patterns and water masses which may affect part of the SIO was studied (New *et al.,* 2005). Little is known on the impact of flow on seasonal physical parameters such as temperature and chlorophyll concentrations (Badal *et al.,* 2009). A study on the dynamics of the flows in the region of the Mascarene Plateau has been conducted by Schott and McCreary (2001) who observed the occurrence of an Ekman divergence due to the north-east monsoon, previously described by Ragoonaden *et al*. (1987), as a divergence zone in the western part of the Plateau.

The subtropical Indian Ocean gyre is dominant in the region (Stramma and Lutjeharms, 1997). The South Equatorial Current (SEC) passes directly through the Mascarene Plateau near 60° E where the current continues and splits into two cores, i.e. the northern and southern core, towards the eastern coast of Madagascar (New *et al.,* 2007). The northern core passes across the Plateau through the channel between the Saya de Malha and Nazareth Banks which may be a significant obstacle to the flow below 200 m depth (New *et al.,* 2007) while the southern core passes through the south of Cargados-Carajdos Bank and north of Mauritius (Bhagooli and Kaullysing, 2019). However, there is sparse information on how the SEC crosses the Plateau or the impact of the flow on the biochemistry of the region (New *et al.,* 2007).

The biogeochemical cycles in the ocean are mainly controlled by biological processes in which nutrients play a major role as indicators for primary productivity. The Indian Ocean accounts for 15 – 20 % of the net primary productivity of the total ocean (Garcia *et al.,* 2018). The Southern Ocean usually receives

http://dx.doi.org/10.4314/wiojms.si2021.2.2

nutrients from the Antarctic Circumpolar Current where high concentrations of phosphate, nitrate and silicate can be found in the surface layer of the polar water; south of the subtropical convergence (Panassa *et al.,* 2018). However, since their primary production could be controlled by the availability of light and trace metals like iron (Fe), these waters show a small vertical gradient in nutrient concentrations (Garcia *et al.,* 2018; Panassa *et al.,* 2018; Grand *et al.,* 2015). The surface waters in most parts of the Indian Ocean are oligotrophic (Jena *et al.,* 2013; Schlüter *et al.,* 2011) due to the presence of a strong upper thermocline which prevents the supply of nutrients from the subsurface to the euphotic zone (Garcia *et al.,* 2018; Resplandy *et al.,* 2009; Gupta and Desa, 2001).

Limited studies on the nutrient distribution have been carried out in the southern Indian Ocean, most specifically on the Mascarene Plateau. The Plateau is considered to be the largest fishing bank (Munbodh, 2014) and major source of frozen fish for the Mauritian market, representing around 30 % of total fish consumption, where most fish are caught at a depth of 0 –100 m at Saya de Malha and Nazareth Banks (Bhagooli and Kaullysing, 2019; Degambur and Sólmundsson, 2005; Ardill, 1986). Thus, studies on the nutrient distribution in the water column on the Mascarene Plateau are of great importance.

The present study aimed at determining the distribution of nutrients across the Saya de Malha and Nazareth Banks. It was also attempted to correlate nutrient distribution with dissolved oxygen and chlorophyll-*a* (chl-*a*) at the Saya de Malha and eastern part of the Nazareth Banks.

Materials and methods

Study site

Data for this study were collected in May 2018 during an expedition on board the R/V Fridtjof Nansen (2018 EAF-Nansen programme) in the region of Saya de Malha and the eastern slope of the Nazareth Banks located in the SIO. The study area covers the region of Saya de Malha from 09°S to 12°S and 59°E to 62°E and the eastern slope of Nazareth Bank from 13°S to 15°S and 60°E to 61°E (Fig. 1). The Mascarene Plateau is a submarine plateau located in the Western Indian Ocean around 2300 km south of the equator (Fisher *et al.,* 1967; Payet, 2005); lying between Seychelles (4°S, 56°E) and Mauritius (20°S, 57°E). The Mascarene Plateau consists of chain of shallow banks (also known as shoals) that form a crescent-like feature from north to south, separated by deeper channels (Payet, 2005). The Saya de Malha Bank (North and South banks), located between 8°30'S - 12°0'S and 59°30'E - 62°30'E (Vortsepneva, 2008), is the largest fishing bank in the plateau with an area of 40,000 km^2 (Betzler *et al.,* 2021). The seabed is jointly managed by the Republic of Mauritius and the Republic of Seychelles by a Commission established under the United Nations Convention on the Law of the Sea. The southern bank is the focus of this study.

The Nazareth Bank is part of the Exclusive Economic Zone of 2.3 million km^2 (excluding the Saya de Malha bank) of the Republic of Mauritius and is situated south of the Saya de Malha Bank separated by a 100 km channel with a depth of around 1100 m (New *et al.,* 2007).

in situ measurement and sample collection

The vertical profiles of temperature, salinity and conductivity were obtained by a Seabird SBE 9 CTD probe. Twelve 10L-Niskin bottles attached to the CTD rosette were used to collect water at predefined depths along the hydrographical transects. The standard sampling depths were set at: 2000, 1700, 1500, 1200, 1000, 750, 500, 400, 300, 200, 100, 75, 50, 25 and 5 m (Table 1).

In total, 145 seawater samples at 27 CTD stations in Saya de Malha Bank and 21 seawater samples at 7 CTD stations in Nazareth Bank were collected in duplicates from the Niskin bottles for the measurement of nutrients. Once seawater samples were collected from the Niskin bottles, they were filtered through a nylon membrane syringe filter of pore size 0.2 µm in a PE tube (30 mL) and immediately stored at -20 °C during the cruise pending measurements.

The CTD was also equipped with sensors measuring chl-*a* (Chelsea Aquatracka III) and dissolved oxygen (SBE 43) in the water column.

Nutrient analyses

Nutrient analysis of seawater samples was carried out in the laboratory at the Mauritius Oceanography Institute. The concentration of nutrients (phosphate, PO_4^{3-}; nitrate, NO_3^-; nitrite, NO_2^-; ammonia, NH_4^+ and silicate, SiO_4^{4-}) in the water column was determined using standard colorimetric analysis (Grasshoff *et al.,* 2009) on an automated nutrient analyser equipped with a 5 cm absorbance reading unit (SYSTEA Easychem Plus) following recommended protocols supplied by the equipment manufacturer. Deionised water and filtered seawater (low nutrient) were used for sample preparation and analyses. For reproducibility of nutrient measurements between analyses, in-house standards were used which were regularly compared with certified reference materials for nutrients in seawater.

Phosphate determination is based on the molybdenum blue method described by Murphy and Riley (1962). In acidic medium, phosphate present in the samples reacts with ammonium molybdate and potassium antimony tartrate to form an antimony-phospho-molybdate complex which is further reduced to an intensely coloured molybdenum blue complex by ascorbic acid where it is measured at 880 nm.

Nitrate is determined by the reduction of nitrate to nitrite with a cadmium reduction column incorporated in the automated nutrient analyser. Nitrite reacts with sulfanilamide under acidic conditions to form a diazonium compound which in turn couples with N-(1-Naphthyl)-ethylenediamine dihydrochloride to form a coloured azo dye complex; measured at 543nm (Strickland and Parsons 1968). The determination of ammonia employs an indophenol-blue reaction between ammonia, phenol and hypochlorite in an alkaline medium described by Grasshoff *et al.* (1972). The indophenol colorimetric reaction is modified by the introduction of the catalyst nitroprusside which accentuates the blue colour at room temperature where the absorbance is measured at 630 nm.

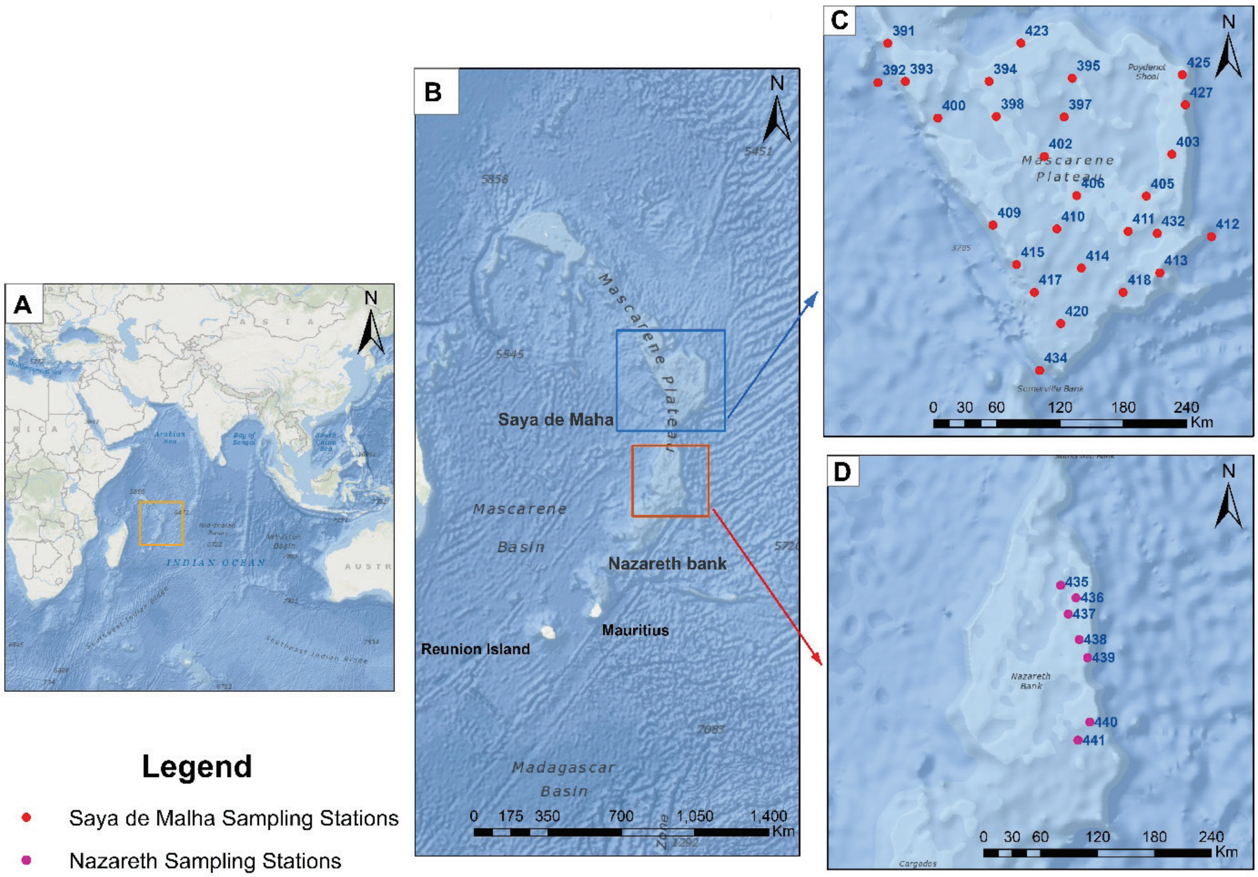

Figure 1. A: Map of the Indian Ocean showing location of the study; B: Study sites at Saya de Malha and Nazareth Banks; C: Sampling sites at Saya de Malha Bank; D: Sampling sites at Nazareth Bank.

Silicate is determined by the reduction of silicate-molybdate by ascorbic acid in acidic medium based on the method described by Koroleff (1972). Oxalic acid is added before addition of ascorbic acid to prevent interference of phosphate in the samples.

Ammonia and nitrite concentrations were below detection limit. The relative error of duplicate sample measurements was on average below 2 % and the detection limit was < 0.2 μm for NH_4^+, < 0.1 μm for NO_2^-, < 0.05 μm for PO_4^{3-}, < 0.08 μm for NO_3^-, and < 0.07 μm for SiO_4^{4-}.

Table 1. Predefined depths down the water column at different bottom-depth stations on board the RV Fridtjof Nansen.

Stations	Defined depth for water sampling from sea surface
Shallow (bottom-depth < 30 m)	5, 25
Intermediate (bottom-depth < 100 m)	100, 75, 50, 25, 5
Deep stations (bottom-depth < 500 m)	500, 400, 300, 200, 100, 75, 50, 25, 5
Extra deep (bottom-depth > 1000 m)	1000, 750,500, 400, 300, 200, 100, 75, 50, 25, 5

Calculations, graphical plots and statistical analysis

Oxygen gas solubility was calculated as a function of *in situ* temperature, salinity and one atmospheric of total pressure using the equation of Garcia and Gordon (1992) and oxygen solubility coefficient values of Benson and Krause (1984). The oxygen saturation was calculated as percentage by dividing the concentration of oxygen in the samples by the oxygen solubility. Depth profiles were been built up for temperature, salinity, dissolved oxygen, nutrients and chl-*a* by calculating the average mean at each standard depth: 5, 25, 50, 75, 100, 200, 300, 400, 500, 750, 1000, 1500, 2000 m. The statistical analysis was carried out using GraphPad Prism version 8.4.3 software (San Diego, California, USA). For statistical analysis, the data was first tested for normality where non-normally distributed data were converted. The one-way ANOVA was used to determine any significant differences between the stations at Saya de Malha and Nazareth Banks, respectively, and two-way ANOVA was used to determine any significant differences with depth for

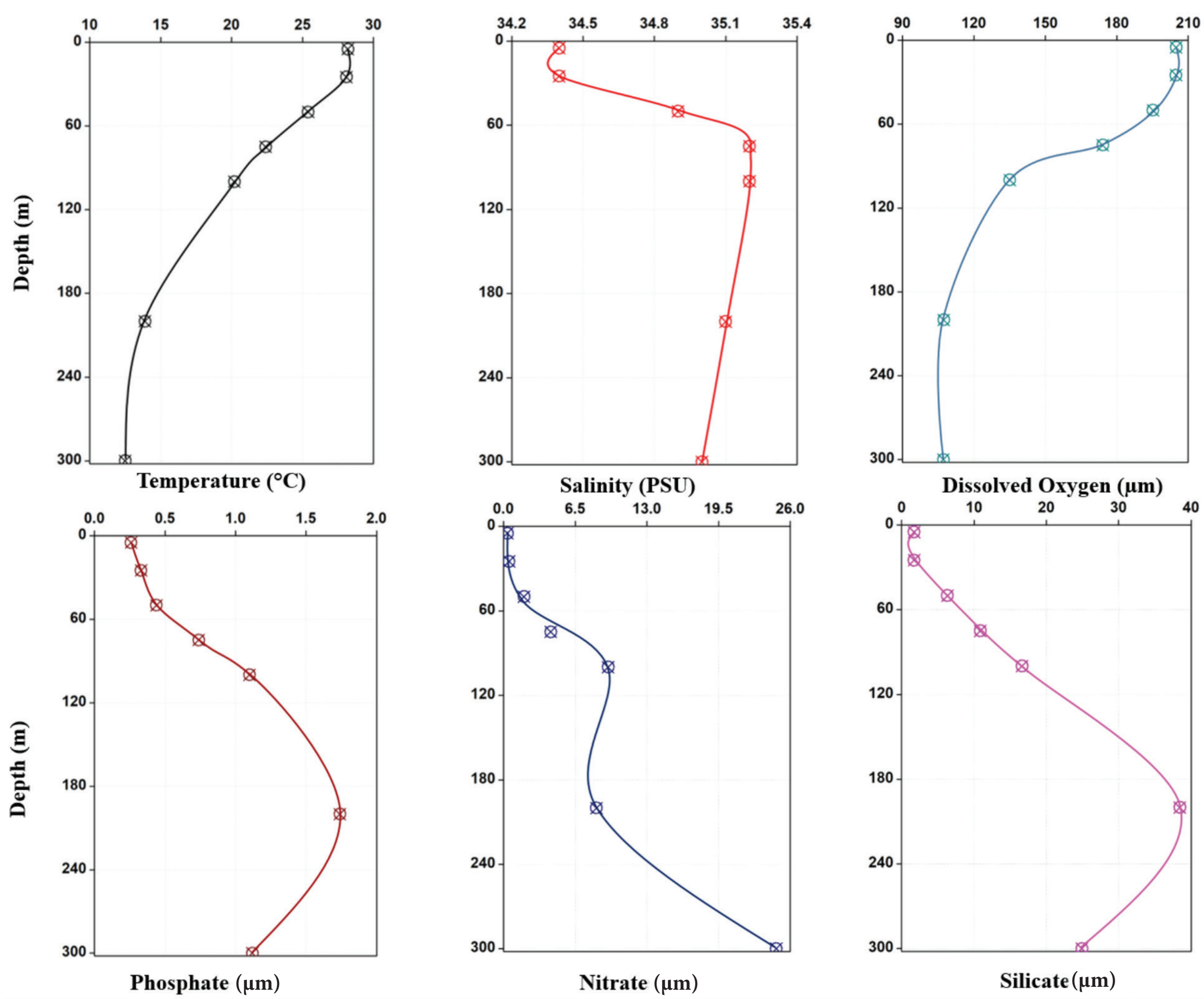

Figure 2. Vertical profiles at the Saya de Malha Bank illustrating the changes with depth of common parameters temperature, salinity, dissolved oxygen, phosphate, nitrate and silicate.

nutrients. Pearson's correlation coefficient was used to determine the correlation between the nutrients with dissolved oxygen and chl-*a*.

Results

The distribution of nutrients is usually affected by the physical dynamics of the ocean. The physical characteristics of the study regions were briefly studied in order to further understand the distribution of nutrients at the Saya de Malha and Nazareth Banks.

Concentration depth profile

Figures 2, 3 and 4 show the depth profiles of temperature, salinity, dissolved oxygen, phosphate, nitrate and silicate on the Saya de Malha and eastern slope of the Nazareth Banks. The bottom depths on the Saya de Malha plateau varied from 26 (CTD 403) to 380 m (CTD 432) at 24 sampling stations, and for the three sampling stations (CTD 392, 412 and 434) in deeper waters around the plateau, the bottom depths varied from 1068 to 2347 m. At the Nazareth Bank, the bottom depths ranged from 31 (CTD 437) to 242 m (CTD 441). The sampling depths at Saya de Malha ranged from 5 to 300 m, and for the deeper stations ranged from 5 to 2000 m, and 5 to 100 m for the Nazareth Bank.

On the Saya de Malha plateau, a surface temperature of 28 °C was observed in the upper 50 m which decreased down the water column to 12.5°C. The upper 25 m displayed a minimum salinity with values of 34.2 to 34.5 PSU which gradually increased to 35.0 PSU. The water column showed a stable stratification where the pycnocline occurred at around 30 to 50 m. The concentration of dissolved oxygen decreased gradually with increasing depth from 205 to 107.2 µm. Phosphate [PO_4^{2-}], nitrate [NO_3^-] and silicate [SiO_4^{4-}] showed the typical nutrient depth profile, with low concentrations on the surface which increases with depth. [PO_4^{2-}], [NO_3^-] and [SiO_4^{4-}] ranged from 0.26 to 1.12 µm, 0.14 to 24.74 µm and 1.56 to 29.94 µm

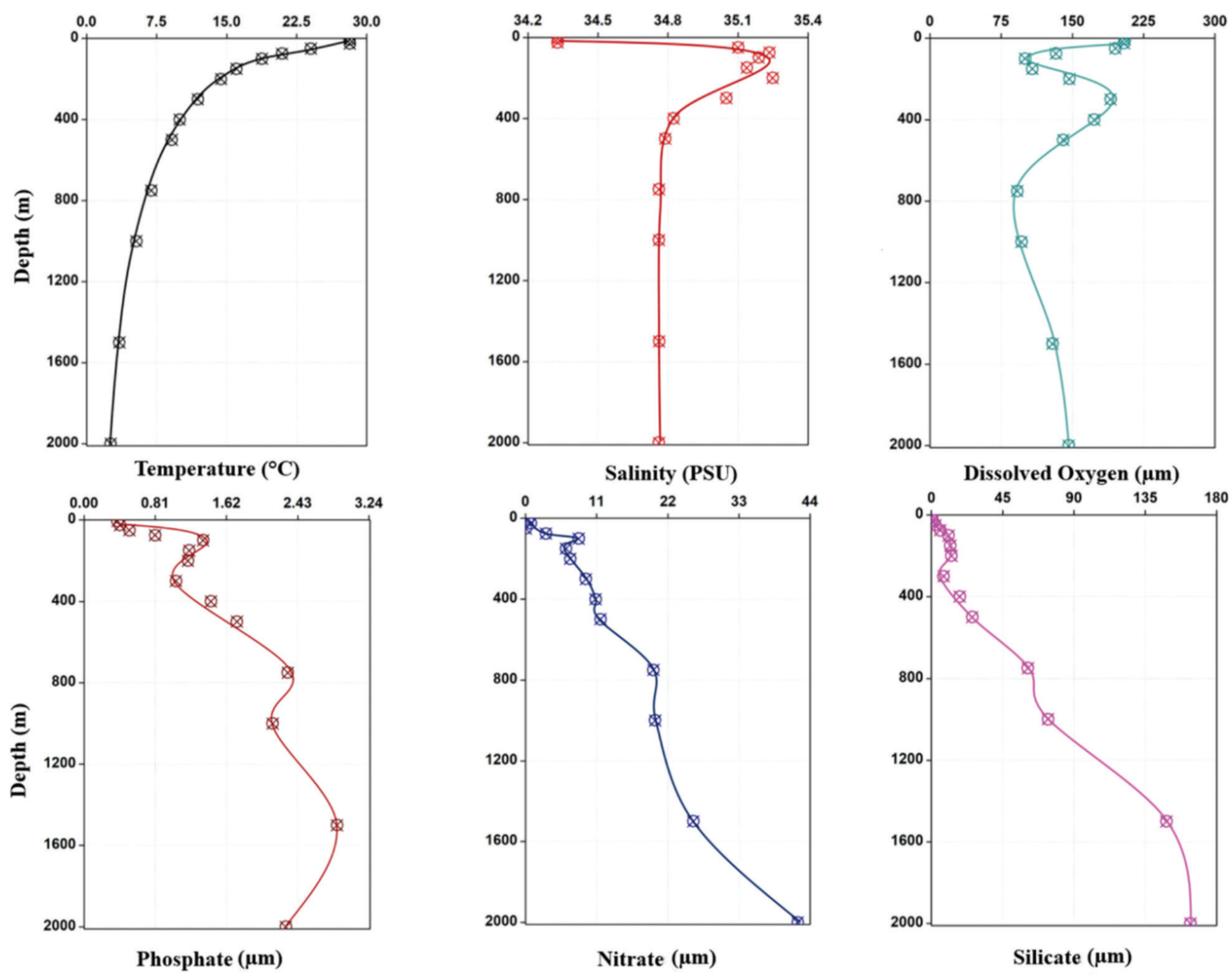

Figure 3. Vertical profiles in the deeper waters around the Saya de Malha plateau illustrating the changes with depth of temperature, salinity, dissolved oxygen, phosphate, nitrate and silicate.

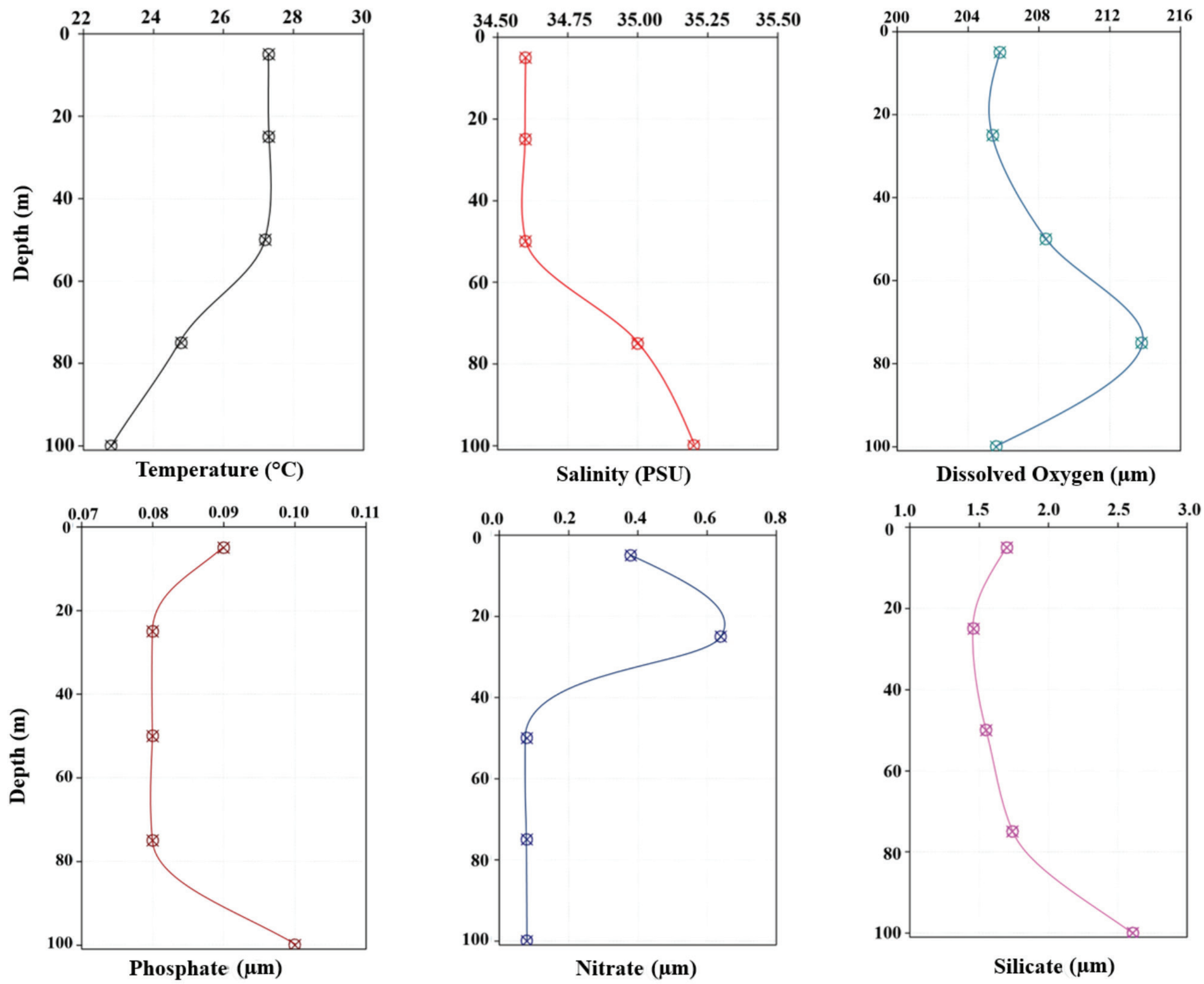

Figure 4. Vertical profiles at the eastern slope of Nazareth Bank illustrating the changes with depth of temperature, salinity, dissolved oxygen, phosphate, nitrate and silicate.

respectively. In general, the concentration of chl-*a* showed a decrease down the water column, ranging from 0.27 to 0.02 µg/l. However, an increase in chl-*a* (0.27 µg/l) was recorded at 50 m.

At the deeper stations, the surface temperature of 28 °C in the upper 50 m was also recorded depicting the presence of warm surface water, decreasing gradually to 2.6 °C. Salinity varied from 34.3 to 34.8 PSU, with an increase to 35.2 between 75 to 100 m. The pyncnocline at the deeper stations was observed between 50 to 150 m. The dissolved oxygen varied from 205.2 to 146.1 decreasing down the water column, but increased from 150 to 300 m, ranging from 107.9 to 190.3 µm. The oxygen minimum layer was found between 100 to 150 m. Similar to the plateau, the nutrients and chl-*a* follow the same pattern, i.e., increasing in with depth. Moreover, an increase of chl-*a* (0.4 µg/l) was also observed at 50 m. In comparison to the plateau, higher concentrations of nutrients and lower concentration of chl-*a* were observed in the deeper waters where the concentration of [PO_4^{2-}], [NO_3^-], [SiO_4^{4-}] and [chl-*a*] ranged from 0.4 to 2.3 µm, 0.4 to 42.1 µm, 0.6 to 163.6 µm, 0.6 to 0.2 µg/l, respectively.

On the eastern slope of Nazareth a small variation in temperature and salinity was found, gradually decreasing from 27.3 to 22.8°C and increasing from 34.6 to 35.2 PSU, respectively. The pycnocline was also observed at 50 m. The oxygen concentration was almost homogenous at different depths in the water column, ranging from 205.8 to 213.8 µm. The concentration of [PO_4^{2-}] was below the detection limit. [NO_3^-] and [SiO_4^{4-}] ranged from 0.2 to < 0.08 and 1.7 to 2.61 µm. The chl-*a* concentration varied from 0.05 to 0.17 µg/l down the depth, with an increase of 0.23 µg/l at 75 m. Overall, the eastern slope of Nazareth Bank exhibited lower concentrations compared to

Table 2A. Ranges of temperature, salinity, dissolved oxygen (DO), density, phosphate, nitrate, silicate and chlorophyll-*a* concentrations in the shallow water column of the Saya de Malha plateau.

Depth (m)	Temperature (°C)	Salinity (PSU)	DO (µm)	Density (kg/m³)	Phosphate (µm)	Nitrate (µm)	Silicate (µm)	Chl-a (µg/l)
5	28.0 - 28.5	34.2 - 34.5	201.5 - 208.0	21.7 - 22.0	0.1 - 0.7	0.1 - 0.4	0.1 - 2.9	0.0 - 0.1
25	28.0 - 28.5	34.2 - 34.5	201.0 - 207.3	21.7 - 22.0	0.1 - 0.8	0.1 - 1.6	0.1 - 3.4	0.0 - 0.2
50	22.7 - 28.1	34.2 - 35.2	172.5 - 223.6	21.8 - 24.2	0.1 - 1.3	0.1 - 7.4	0.1 - 7.5	0.0 - 0.5
75	20.7 - 23.7	35.1 - 35.3	131.5 - 212.5	23.8 - 24.7	0.1 - 1.5	0.1 - 7.4	1.6 - 13.1	0.2 - 0.3
100	18.4 - 21.7	35.1 - 35.4	104.6 - 176.3	24.4 - 25.4	0.3 - 2.4	0.1 - 16.4	2.3 - 18.9	0.1 - 0.2
200	13.9	35.1	107.4	26.3	1.7	8.4	38.5	0.03
300	12.5	35.0	107.2	26.5	1.1	24.7	24.9	0.02

Table 2B. Ranges of temperature, salinity, dissolved oxygen (DO), density, phosphate, nitrate, silicate and chlorophyll-*a* concentrations in the deeper water column around Saya de Malha plateau.

Depth (m)	Temperature (°C)	Salinity (PSU)	DO (µm)	Density (kg/m³)	Phosphate (µm)	Nitrate (µm)	Silicate (µm)	Chl-a (µg/l)
5	27.8 - 28.4	34.2 - 34.5	204.1 - 206.6	21.7 - 21.9	0.1 - 0.7	0.1 - 1.1	0.1 - 1.3	0.0 - 0.08
25	27.8 - 28.4	34.2 - 34.5	203.9 - 205.5	21.7 - 21.9	0.1 - 0.6	0.1 - 2.3	0.1 - 1.8	0.0 - 0.08
50	24	35.1	189.7 - 200.9	23.7	0.2 - 0.8	0.1	1.1 - 3.9	0.4
75	20.5 - 21.4	35.2 - 35.3	132.0 - 133.8	24.5 - 24.8	0.5 - 1.1	0.1 - 6.3	2.7 - 8.6	0.1 - 0.2
100	18.2 - 19.6	35.2	88.5 - 111.0	25.0 - 25.4	0.9 - 1.7	0.1 -16.9	3.3 - 15.7	0.1
150	15.3 - 16.8	35.0 - 35.2	84.3 - 131.5	25.7 - 26.0	0.6 - 1.8	0.1 - 12.5	7.4 - 16.7	0.02
200	13.4 - 15.6	35.1 - 35.4	104.5 - 187.3	26.2 - 26.4	0.4 - 1.9	0.08 - 11.6	4.2 - 26.1	0.0 - 0.02
300	11.9	35.0 - 35.1	183.4 - 197.2	26.6 - 26.7	0.8 - 1.3	0.08 - 18.6	2.4 - 13.1	0.0 - 0.01
400	9.7 - 10.3	34.8	152.7 - 192.6	26.8	0.5 - 2.0	0.08 - 20.5	4.5 - 31.6	0.0 - 0.02
500	9.1 - 9.3	34.8	119.7 - 163.1	26.9 - 27.0	0.6 - 2.3	0.3 - 22.4	10.9 - 40.5	0.02
750	6.6 - 7.4	34.7 - 34.8	87.0 - 94.7	27.2 - 27.3	1.6 - 3.0	0.7 - 31.7	19.6 - 92.1	0.02
1000	5.1 - 5.6	34.7 - 34.8	88.2 - 102.7	27.4 - 27.5	1.3 - 3.1	0.4 - 33.6	24.4 - 118.1	0.02
1500	3.5	34.8	129.2	27.7	2.9	26	148.4	0.02
2000	2.6	34.8	146.1	27.7	2.3	42.1	163.6	0.01

Table 2C. Ranges of temperature, salinity, dissolved oxygen (DO), density, phosphate, nitrate, silicate and chlorophyll-*a* concentrations in the water column of the eastern slope of Nazareth Bank.

Depth (m)	Temperature (°C)	Salinity (PSU)	DO (µm)	Density (kg/m³)	Phosphate (µm)	Nitrate (µm)	Silicate (µm)	Chl-a (µg/l)
5	27.2 - 27.3	34.5 - 34.6	202.8 - 209.1	22.3	< 0.1	< 0.08 - 0.2	1.5 - 1.8	0.0 - 0.1
25	27.2 - 27.3	34.5 - 34.6	202.4 - 208.9	22.3	< 0.1	< 0.08	0.9 - 1.7	0.0 - 0.1
50	27.1 - 27.2	34.6	207.6 - 209.3	22.3 - 22.4	< 0.1	< 0.08	1.2 - 1.9	0.07
75	25.3 - 24.4	34.9 - 35.1	210.1 - 217.5	23.2 - 23.6	< 0.1	< 0.08	1.4 - 2.1	0.2
100	23.0 - 22.6	35.2 - 35.3	204.4 - 206.8	24.1 - 24.3	< 0.1	< 0.08 - 0.1	1.9 - 3.3	0.2

the Saya de Malha Bank. Tables 2A-C show the range of temperature, salinity, dissolved oxygen and density, [PO_4^{2-}], [NO_3^-], [SiO_4^{4-}] and [chl-*a*] concentrations on the Saya de Malha plateau, deeper waters around Saya de Malha Bank and the eastern slope of the Nazareth Bank.

T-S profile

Figure 5 shows detailed temperature-salinity (T-S) profiles down the water column in the deeper waters at the deep CTD stations around the Saya de Malha plateau (Table 3), on the Saya de Malha plateau and Nazareth Bank.

The water mass distribution at the Saya de Malha Bank was characterised based on New *et al.*, (2007) and Emery (2005). Four water masses were identified in the upper 500 m. Low salinities ranging from 34.2 to 34.5 PSU and high temperatures ranging from 27.8 to 24.8 °C were observed in the surface water mass (Table 2B).

Table 3. Details of water samples collected with a CTD for nutrient analysis in the study areas.

Site	Station	Date	Time/UTC	GPS Location		Bottom Depth (m)	Nutrients	CTD
				Latitude (S)	Longitude (E)			
Saya de Malha plateau	391	7-May-18	14 00	09 47.50	059 43.90	131	√	√
	393	8-May-18	01 17	10 07.18	059 52.08	74	√	√
	394	8-May-18	10 00	10 06.79	060 34.51	27	√	√
	395	8-May-18	16 06	10 05.43	061 16.83	29	√	√
	397	9-May-18	11 20	10 24.88	061 12.75	68	√	√
	398	9-May-18	16 09	10 24.73	060 37.93	60	√	√
	400	10-May-18	01 42	10 25.62	060 08.38	51	√	√
	402	10-May-18	16 42	10 45.39	061 02.70	128	√	√
	403	11-May-18	02 42	10 43.91	062 07.79	26	√	√
	405	11-May-18	13 43	11 05.54	061 55.17	52	√	√
	406	11-May-18	19 22	11 04.98	061 19.39	120	√	√
	409	12-May-18	01 52	11 19.98	060 36.53	195	√	√
	410	12-May-18	13 53	11 21.96	061 09.33	156	√	√
	411	12-May-18	19 52	11 23.53	061 45.57	109	√	√
	413	13-May-18	06 35	11 44.65	062 02.11	284	√	√
	414	13-May-18	12 01	11 42.35	061 22.04	248	√	√
	415	13-May-18	17 48	11 40.49	060 48.52	265	√	√
	417	14-May-18	00 06	11 55.02	060 58.00	328	√	√
	418	14-May-18	06 21	11 55.02	061 42.86	265	√	√
	420	14-May-18	17 07	12 10.55	061 10.93	207	√	√
	423	18-May-18	21 23	09 47.46	060 51.07	110	√	√
	425	20-May-18	22 52	10 03.56	062 13.40	192	√	√
	427	21-May-18	18 07	10 19.17	062 14.73	215	√	√
	432	25-May-18	06 42	11 24.53	062 00.49	380	√	√
Deep Stations around Saya de Malha	392	7-May-18	21 20	10 07.55	059 38.10	2347	√	√
	396	9-May-18	00 31	10 02.80	062 32.99	2172	√	
	399	9-May-18	22:55	10 25.70	059 54.08	1204		√
	401	10-May-18	06 10	10 46.18	059 58.42	2129		√
	404	11-May-18	07 47	10 43.11	062 34.27	2125		√
	408	12-May-18	04 32	11 18.66	060 20.31	2700		√
	412	13-May-18	02 35	11 25.94	062 27.90	2068	√	√
	416	13-May-18	21 17	11 54.52	060 45.63	1309		√
	434	26-May-18	18 27	12 34.55	061 00.43	1068	√	√
Nazareth Bank	435	27-May-18	04 50	13 54.97	060 51.90	43	√	√
	436	27-May-18	06 24	14 02.27	061 00.74	36	√	√
	437	27-May-18	09 22	14 10.85	060 56.47	31	√	√
	438	27-May-18	12 33	14 24.87	061 02.64	32	√	√
	439	27-May-18	14 51	14 34.82	061 07.43	56	√	√
	440	29-May-18	08 03	15 10.42	061 08.64	170	√	√
	441	29-May-18	14 02	15 19.96	061 01.83	242	√	√

Three water masses were identified below the low salinity surface water (LSW), namely the Arabian Sea Water (ASW) found between 50 and 75 m, the Sub Tropical Surface Water (STSW) found at 150 m, and the South Indian Central Water (SICW), found between 300 and 400 m. The maximum temperature, salinity and density in these features occurred at around 20 °C to 23.5 °C, 34.7 PSU to 35.3 PSU, 24 kg/m^3 to 24.5 kg/m^3 for ASW, 15 °C to 18 °C, 35.1 PSU to 35.3 PSU, 26.0 kg/m^3 for STSW, and 8 °C to 10 °C, 34.7 to 35.2 PSU, 26.5 kg/m^3 to 27 kg/m^3 for SICW, respectively.

The bottom or immediate layer (500 to 1500 m) had the same water mass properties as that of the Antarctic Intermediate Water (AIW) characterised with temperatures of 2.0 to 8.0 °C, salinity between 34.6 to 34.7 PSU and density at 27.25 kg/m^3. From the T-S plot for the eastern part (Fig. 5c), an additional water mass was identified as the Indian Equatorial Water (IEW) with water characteristics of 8.0 °C to 23 °C, 34.6 PSU to 35.1 PSU, 24.0 kg/m^3 to 26 kg/m^3 in the upper waters. The T-S plot on the western part had similar water masses as in the overall deep stations (Fig. 5d).

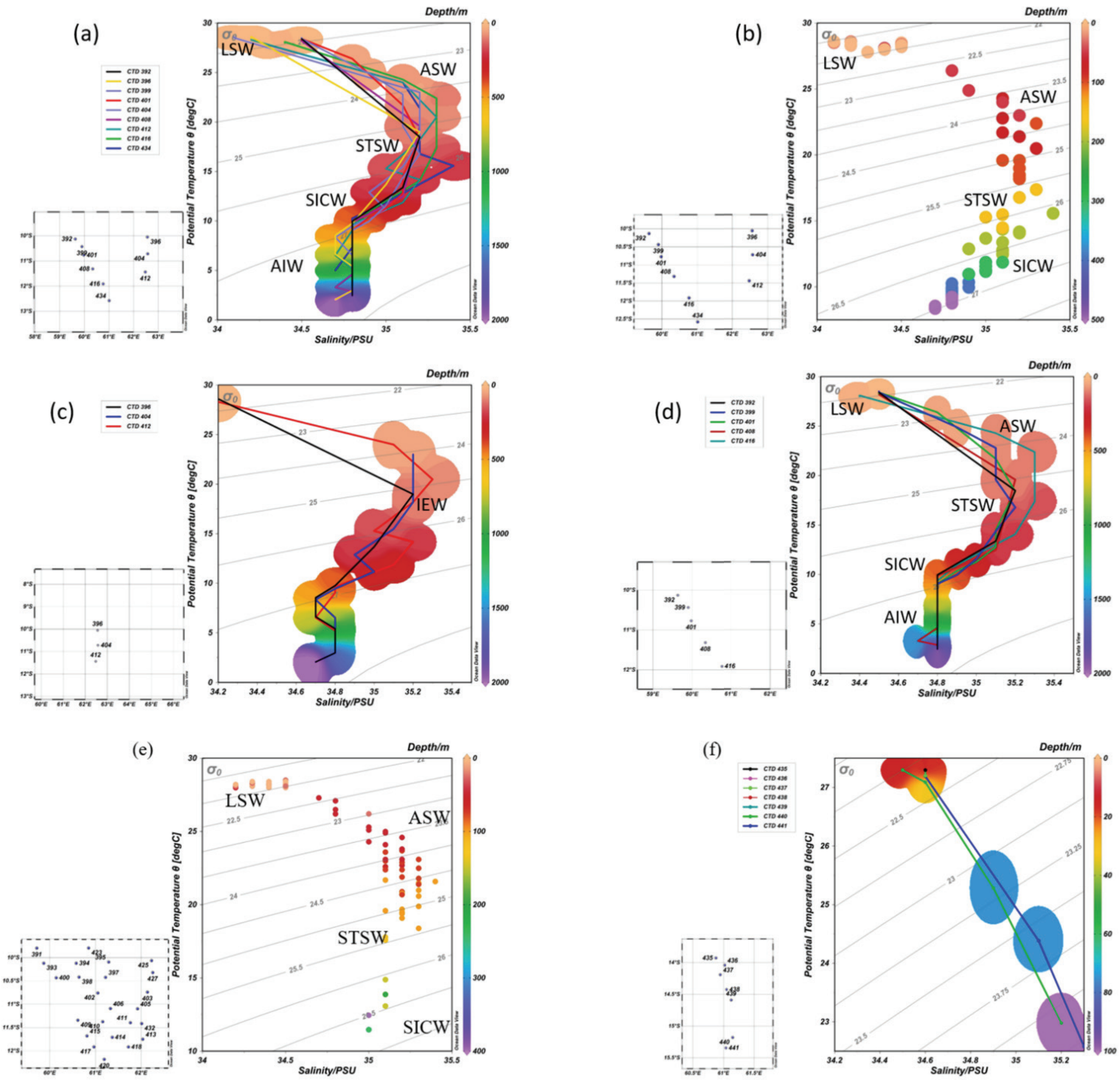

Figure 5. T-S diagram at (a) the deeper stations around the Saya de Malha Plateau, (b) upper 500 m of the deeper stations, (c) eastern part and (d) western part of the deep waters around Saya de Malha, (e) Saya de Malha plateau and (f) eastern slope of Nazareth Bank. Abbreviations are: LSW - Low Salinity Surface Water; ASW - Arabian Sea Water; STSW - Sub Tropical Surface Water; SICW - South Indian Central Water; AIW - Antarctic Intermediate Water; IEW - Indian Equatorial Water. The diagonal lines on the graphs show density in kg/m^3.

As for the Saya de Malha plateau (Fig. 5e), the water masses identified were ASW, STSW and SICW. At the Nazareth Bank (Fig. 5f), small variations in the water characteristics were observed due to insufficient data and the shallowness of the sampling stations. As such, the water mass(es) could not be identified.

Distribution of nutrients across Saya de Malha and Nazareth Banks

As mentioned above, [PO_4^{2-}], [NO_3^-] and [SiO_4^{4-}] show a typical nutrient depth profile which increases with depth. The concentration of phosphate (0.1 to 3.1µm) in general at the Saya de Malha and Nazareth Banks is lower as compared to nitrate (0.1 to 42.1 µm) and silicate (0.1 to 163.6 µm) as shown in Table 2. One-way ANOVA showed no significant differences among the CTD stations ($P > 0.05$). However, at different depths, strongly significant differences were observed for temperature, density, nutrients and chl-*a* ($p < 0.0001$). The nutricline on the Saya de Malha plateau was at around 50 m, similar to the pycnocline, indicating the presence of a mixed layer at that depth. The above mixing layer is depleted

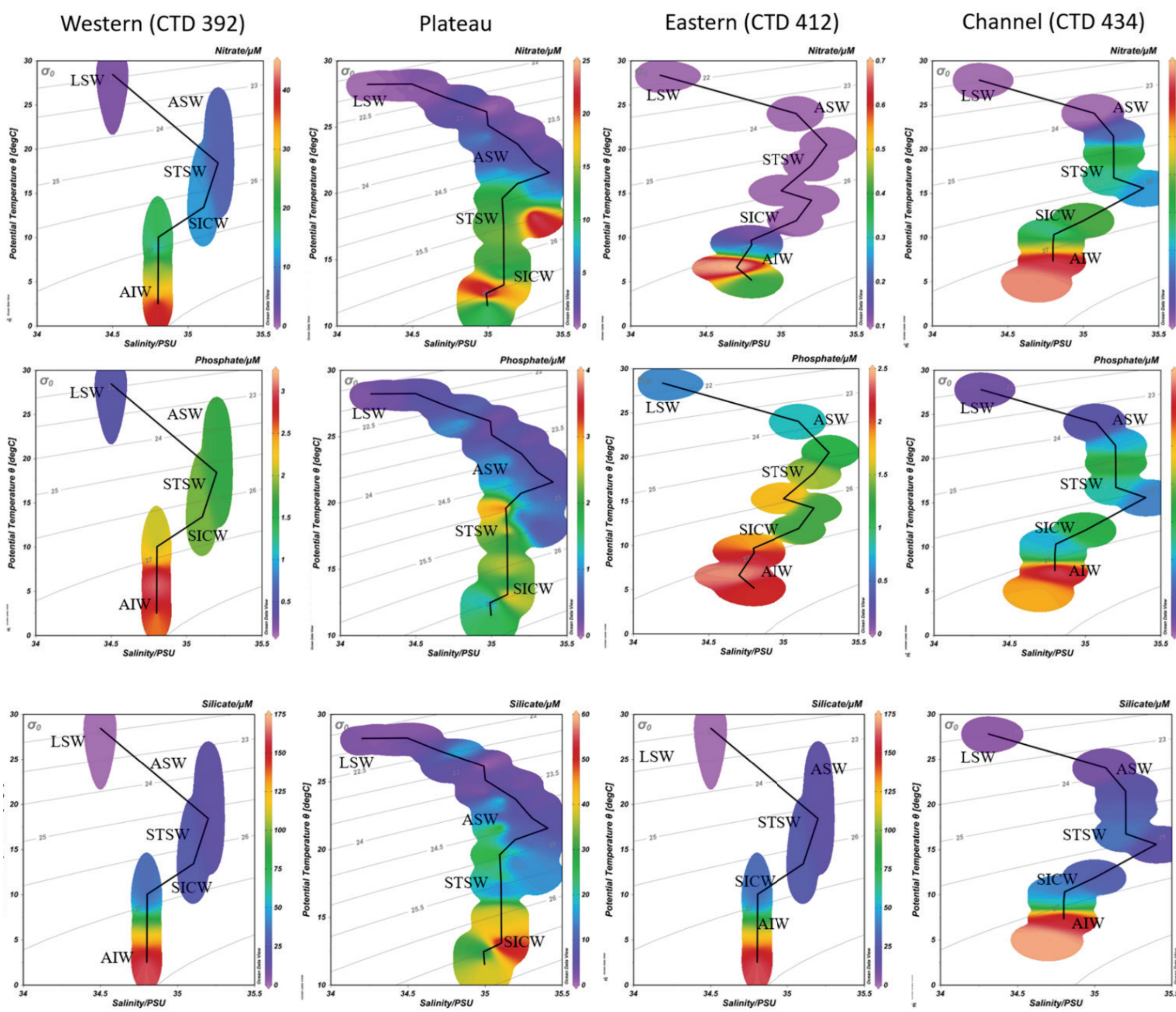

Figure 6. Profile of nutrients (phosphate, nitrate and silicate) at deep CTD stations 392, 412, 434 and Saya de Malha plateau with an overlay of the mass distribution. The diagonal lines on the graphs show density in kg/m³.

in [PO_4^{2-}] (0.2 µm), [NO_3^-] (0.3 µm) and [SiO_4^{4-}] (2 µm) in the depth range of 34.5 to 34.8 PSU (Fig. 2).

In the deeper waters, the nutricline was observed at around 50 to 75 m. The concentration of [PO_4^{2-}] and [NO_3^-] was higher in the deep waters as compared to the plateau where the concentrations were around 1.6 µm and 10 µm. The concentration of [SiO_4^{4-}] was the same as for the plateau. Within the intermediate water (around 800 to 1000 m), phosphate and nitrate was within the range for typical deep waters with values > 30 µm and > 2 µm (Sarmiento and Gruber, 2006).

On the plateau, high concentrations of [PO_4^{2-}], [NO_3^-] and [SiO_4^{4-}], were observed in the STSW and SICW with the highest concentrations of [SiO_4^{4-}] and [NO_3^-] in the SICW, whereas the thermocline water was poor in nutrients (< 5 µm) in the same region. The LWS exhibited low nutrient concentrations of values less than 5 µm (Fig. 6). The northern part of the plateau also showed a higher concentration of nutrients than the southern part (Fig. 7). The different water masses are clearly seen in Figure 7. The concentrations of nutrients was more pronounced from 80 to 100 m on the northern part whereas in the southern part, an increase was seen from 100 to 120 m. The density surfaces seem to have an effect on the nutrients where high levels of nutrients were observed in surfaces denser than 25 kg/m³. The western part of the plateau had higher nutrient concentrations than the eastern plateau.

Due to the shallowness of the plateau, it appeared that the nutrients from the deeper waters are brought to

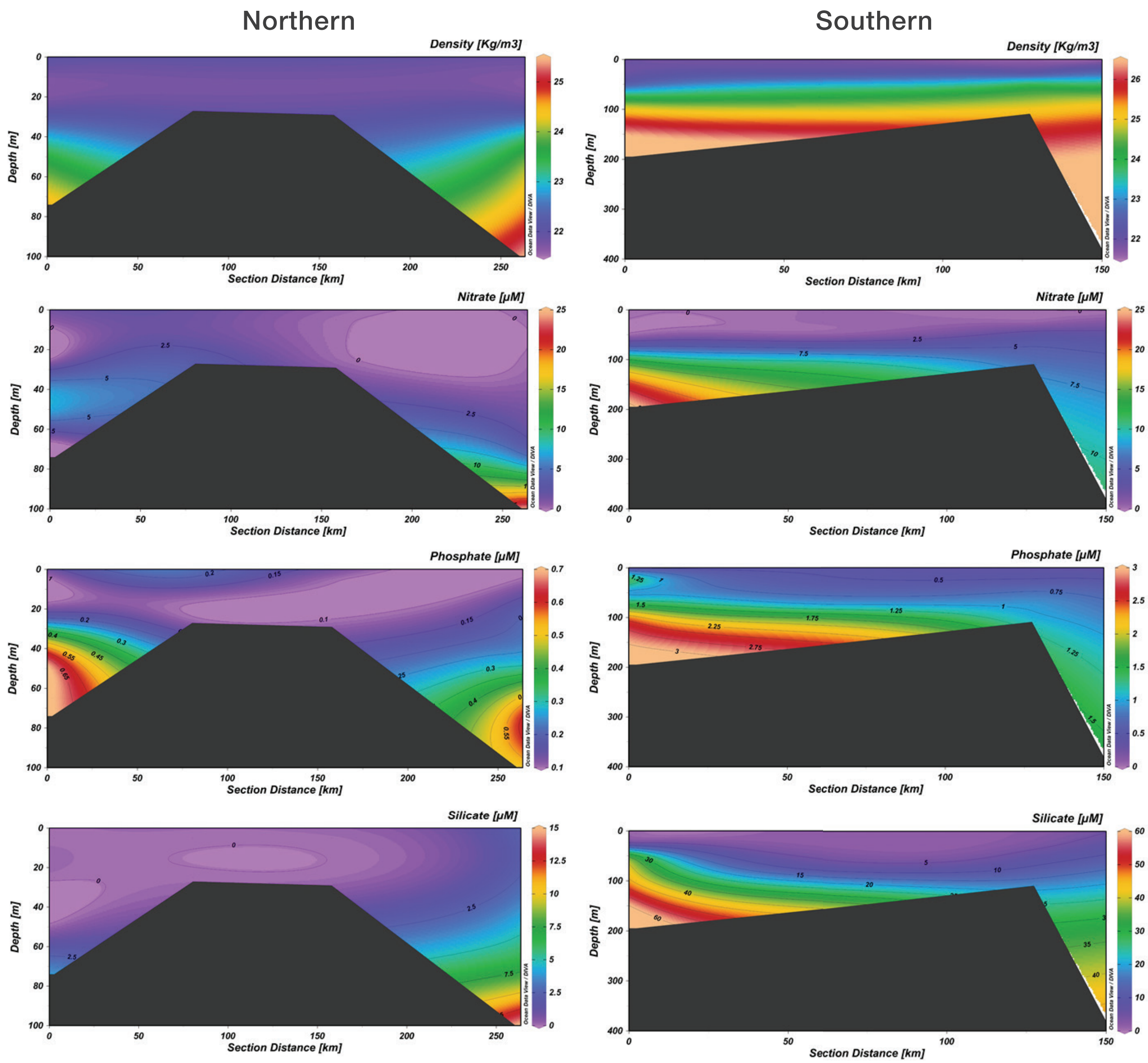

Figure 7. Section plot of nutrients and density from left (0 km) to right (150 km) on the northern and southern part of the Saya de Malha plateau. The northern transect comprised of CTD stations 393, 394, 395 and 425 and the southern transects of CTD stations 409, 410, 411, 432.

the upper waters on the plateau where the water layers on the western plateau are narrower and sharper than the eastern plateau (Fig. 8). The waters coming from the eastern part had much lower nutrient concentrations and a major difference could be seen in [NO_3^-] and [SiO_4^{4-}] with values 1.2 µm and 25 µm at 300 m passing through the plateau to the western part showing an increase to 3.0 µm and 60 µm respectively. This may be due to the upwelling of nutrients onto the plateau where the colder deep water could be seen to be brought to the surface as shown in Figure 8.

In the oceanic region, [SiO_4^{4-}] increased by almost 2.5 times towards the deepest depths (Fig. 6), being lowest in the LWS region to highest in the AIW region (~150 µm – Fig. 6). Similarly, high concentrations of [NO_3^-] were also seen at the western station and in the channel between Saya de Malha and Nazareth Banks. However, at the eastern station, [NO_3^-] was the lowest compared to the other deep stations and on the plateau. [PO_4^{2-}] was uniform in the deep waters and on the plateau. Figure 5 also displays a pattern in the nutrients at the deeper stations. CTD 392 (western) and CTD 412 (eastern) are located in the northern part of the Saya de Malha Bank while CTD 434 (channel) is found in the southern part of the Bank. The concentration of nutrients in the northern part at greater depths was higher than in the southern part. A notable increase was seen in [SiO_4^{4-}] where a major difference in concentrations could be found at

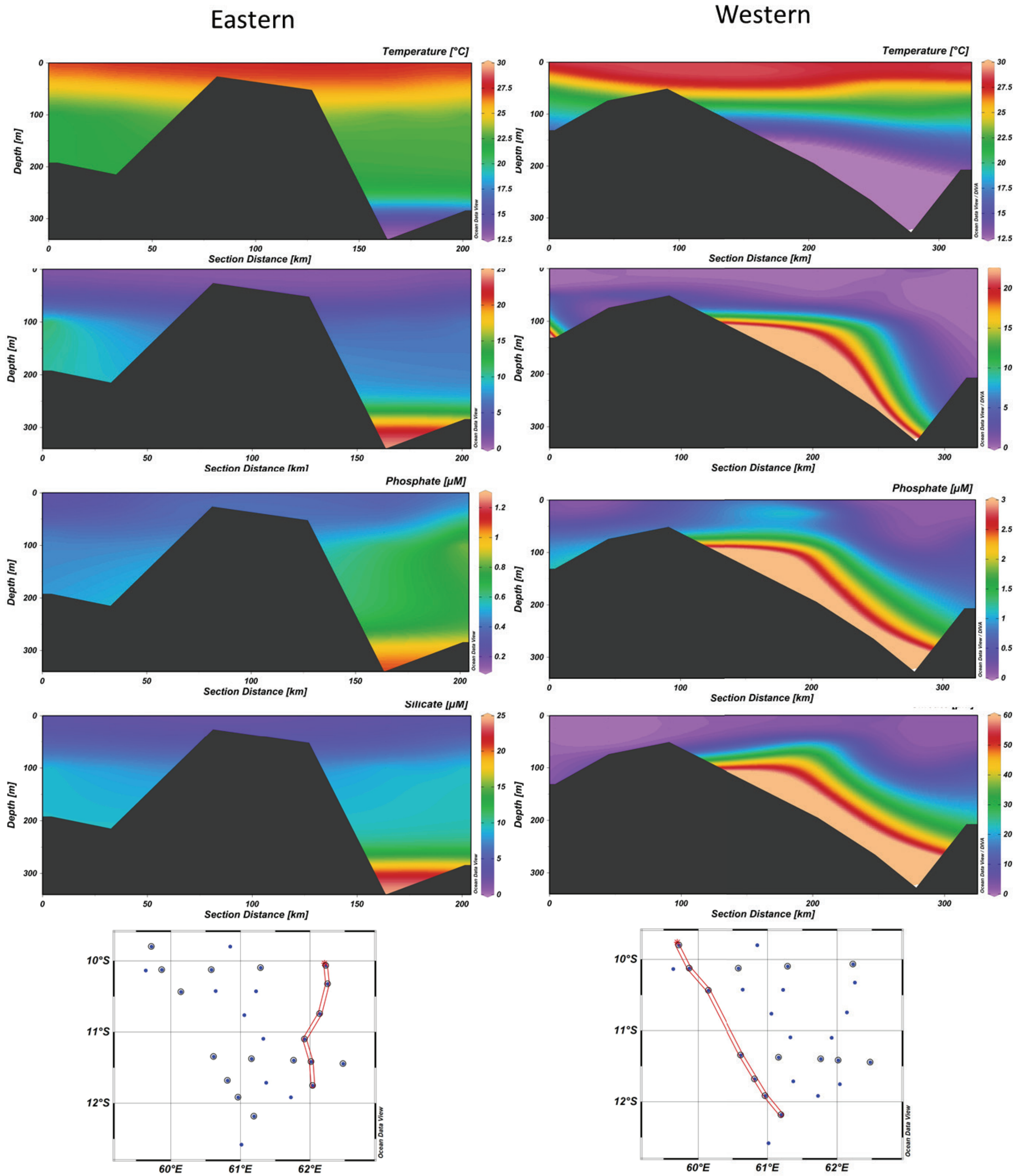

Figure 8. Section plot of nutrients and density from north (0 km) to south (300 km) on the eastern and western part of the Saya de Malha plateau. The eastern transect comprised of CTD stations 425, 427, 403, 405, 432 and 413 and the western transect of CTD stations 391, 393, 400, 409, 415, 417 and 420.

around 150 µm on the northern and 70 µm on the southern region.

At the Nazareth Bank, low concentrations of nutrients were observed as compared to the Saya de Malha Bank (Figs. 3 and 4).

Nutrients with dissolved oxygen and chl-*a*

The concentration of dissolved oxygen (DO) on the Saya de Malha plateau showed variation among the water masses and between transects (northern and southern), ranging between 75 to 220 µm/l. The highest concentrations were associated with LSW

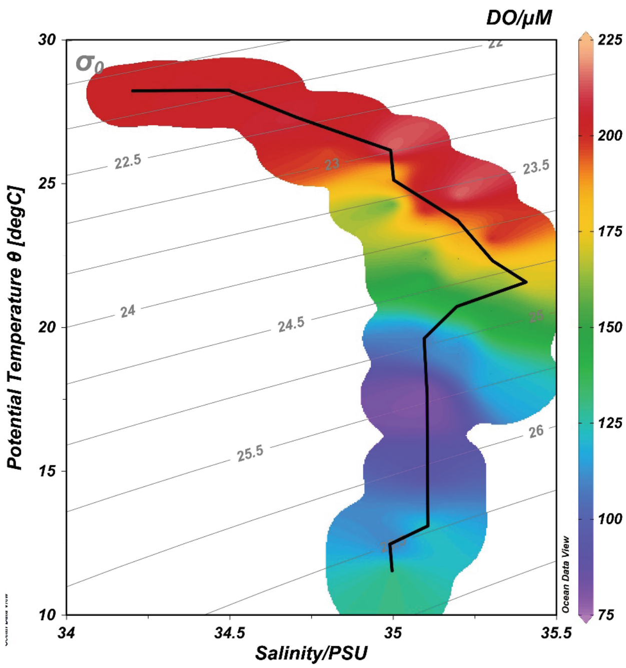

Figure 9. Profile of DO at the SDM plateau with an overlay of the mass distribution. The diagonal lines on the graphs show density in kg/m^3.

and ASW in the upper 100 m and the lowest with the STSW (Figs. 5e and 9). High concentrations of DO was observed in the upper 50 m which decreased below the thermocline (Fig. 10e). The oxygen minimum layer could be observed at the deeper stations where the nutrient maximum is also the same at around 100 m (Fig. 3). The DO concentration (Fig. 10a-d) exhibited minor variations on the plateau and in comparison to the Nazareth Bank.

Correlation between DO along with oxygen saturation and nutrients showed negative R values where a strong correlation (R = -0.7) was observed with [PO_4^{2-}] and [NO_3^-] and a weak correlation with [SiO_4^{4-}]. [SiO_4^{4-}] is absorbed by diatoms; a type of phytoplankton that makes shell from SiO_4^{4-} (Gupta and Desa, 2001). The dissolution of frustules of diatoms attributing an increase in the [SiO_4^{4-}] in the deeper waters does not usually involve the consumption of oxygen (Gupta and Desa 2001; Gupta *et al.*, 1976). Considering the saturation of DO (%) on the plateau (Fig. 11a), most of the stations showed values higher than 92 % between

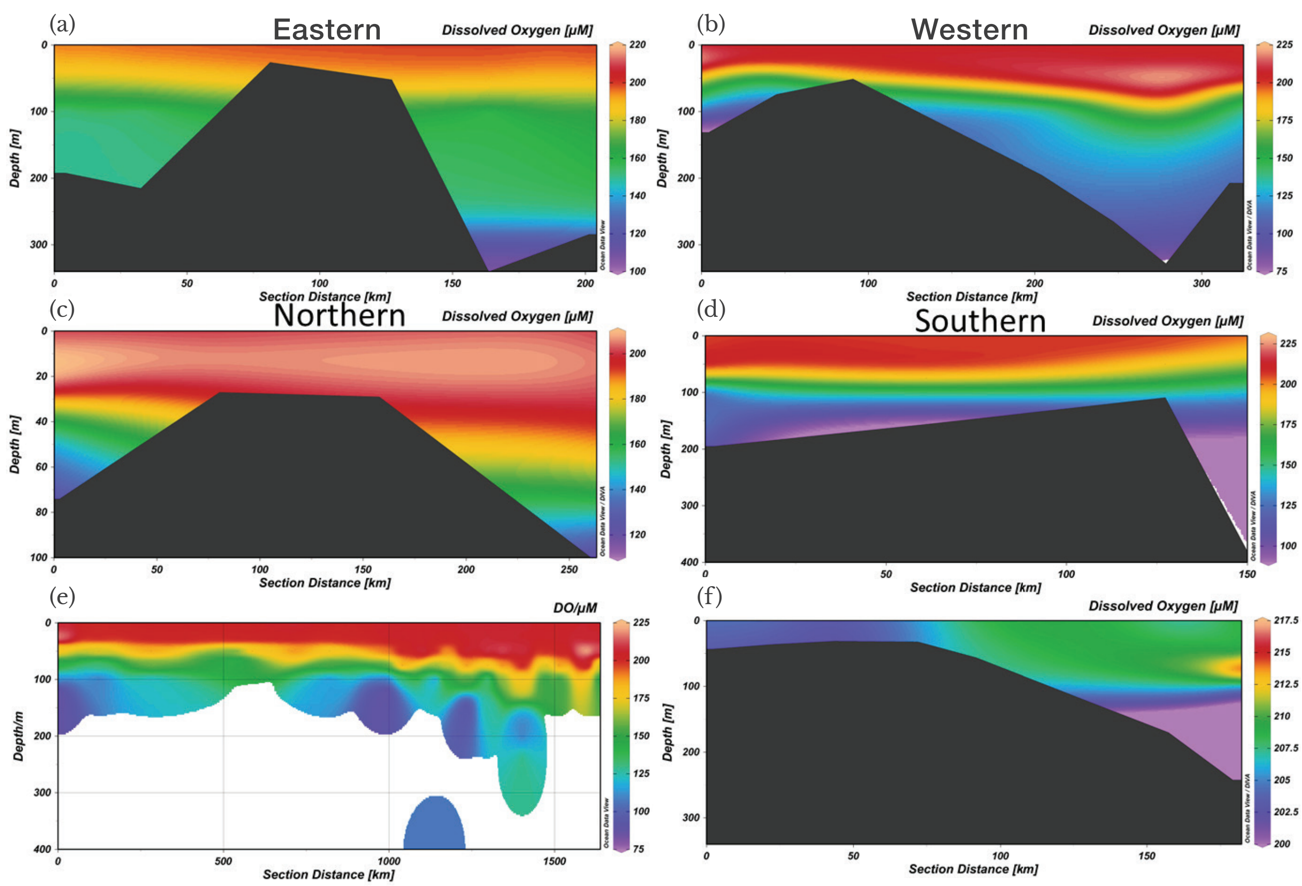

Figure 10. Section plot of dissolved oxygen (μm) on the (a) eastern, (b) western, (c) northern, (d) southern parts, and (e) overall dissolved oxygen distribution at the Saya de Malha plateau and (f) at Nazareth Bank.

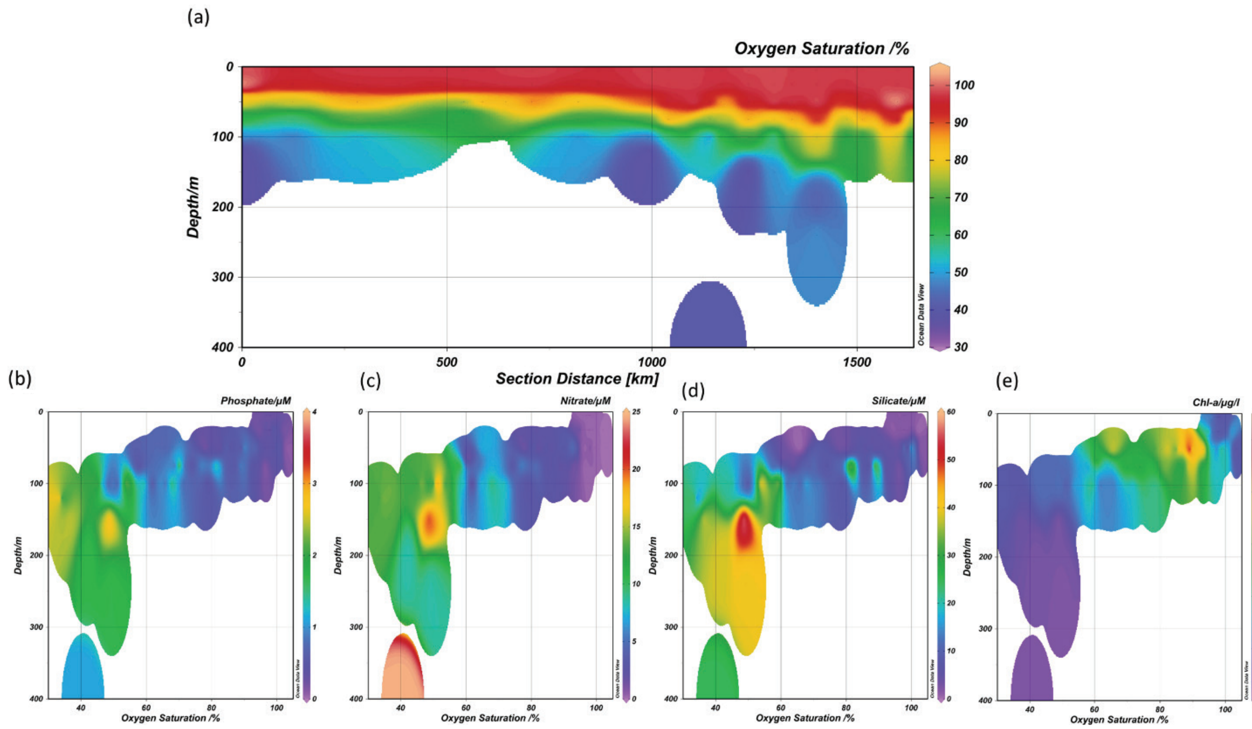

Figure 11. Section plot of oxygen saturation (%) on the plateau of Saya de Malha Bank and its correlation with (b) phosphate, (c) nitrate, (d) silicate and (e) chl-*a* in the water column.

5 to 75 m depth and values lower than 50 % between 100 to 400 m. At Nazareth Bank, the values at all the stations were higher than 94 %. High concentration of nutrients was observed at low - oxygen saturated water between 100 to 200 m (Fig. 11a-c); near the oxygen minimum layer which may be due to the decomposition of organic matter in that region.

Low chl-*a* values were recorded at Saya de Malha and Nazareth Bank where the mean value was found to be 0.13 µg/l and 0.09 µg/l respectively. The chl-*a* values are very low in comparison to the mean global ocean value of 193µg/l (Morel *et al.,* 2010). The low chl-*a* in the region confirms the region being oligotrophic. The deep chlorophyll maximum (DCM) is usually

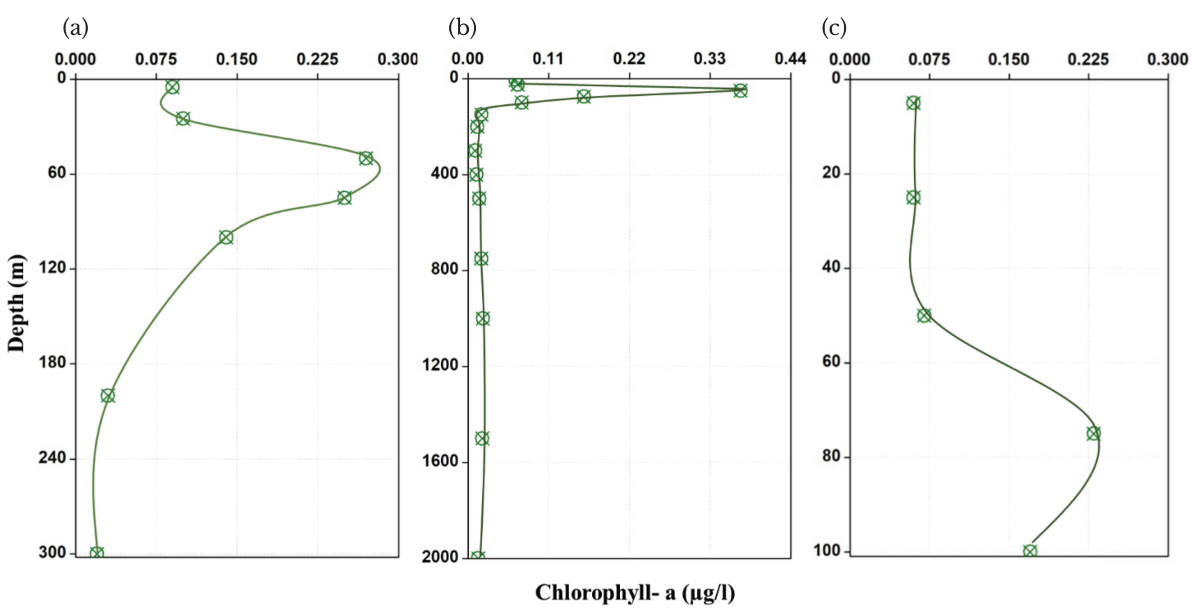

Figure 12. Chlorophyll-*a* profile at (a) Saya de Malha plateau (b) the deep station around Saya de Malha and (c) Nazareth Bank.

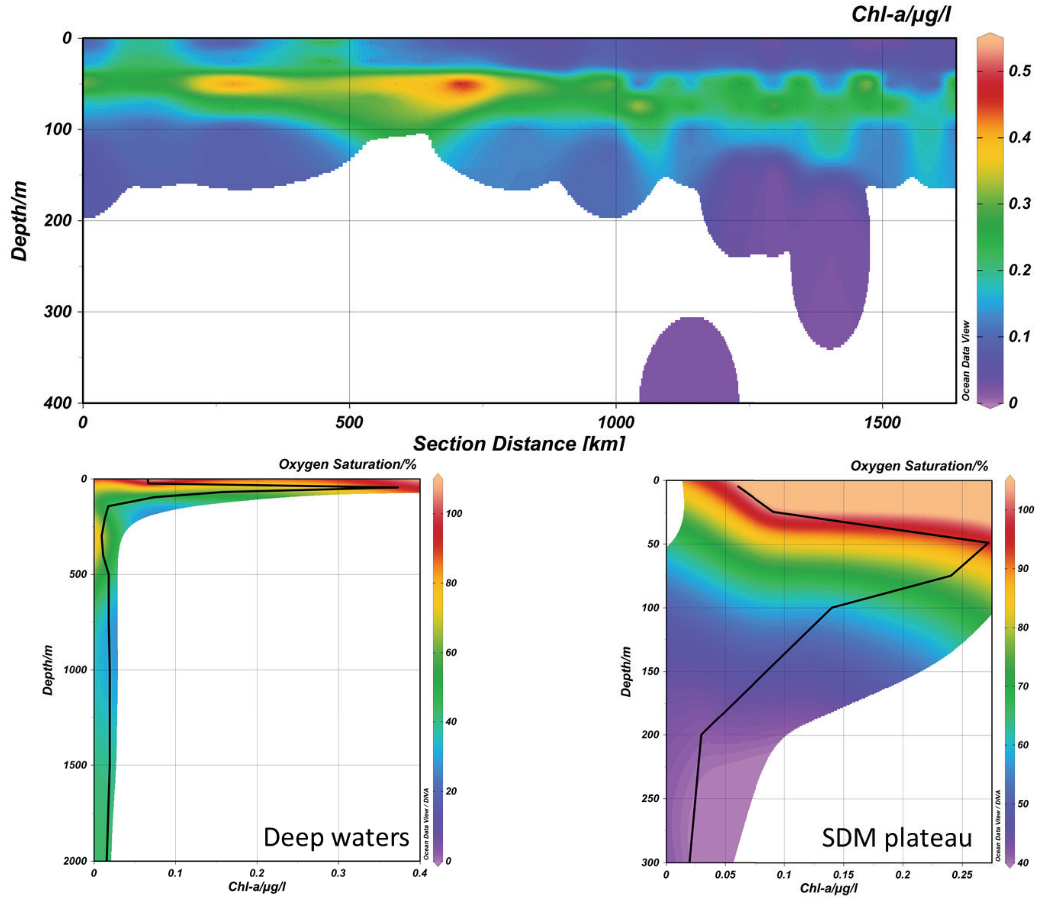

Figure 13. Section plot of Chl-*a* concentration at the Saya de Malha (SDM) plateau in the water column and its correlation with oxygen saturation at the deeper stations around the SDM and stations on the SDM plateau.

found between the upper water (nutrient deficient) and lower water layer (light limited) where it is characterised by high chl-*a* values, thus indicating high phytoplankton biomass (Latasa *et al*., 2017; Li *et al*., 2012). The DCM at the Saya de Malha Bank was found to be at 60 m and around 75 m at the Nazareth Bank where highest chl-*a* values were 0.3 to 0.35 µm and 0.23 µm respectively (Fig. 12).

Chl-*a* showed a correlation with negative R values (R =0.3) with the nutrients, indicating high concentration of chl-*a* present at low concentration of nutrients.

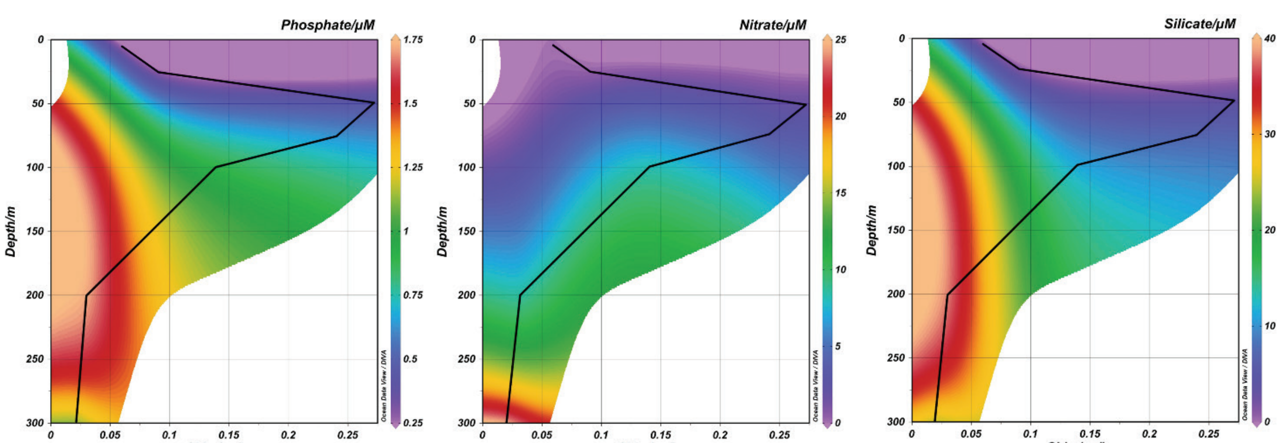

Figure 14. Relationship between nutrients and chl-*a* on the Saya de Malha plateau.

On the plateau, high chl-*a* values between 0.3 to 0.5 µg/l were found at 50 m in the upper layer (Fig. 13). Figure 13 clearly shows photosynthetic activity in the DCM where the oxygen saturation was 100 % and above at a high chl-*a* concentration.

The relationship of [PO_4^{2-}], [NO_3^-] and [SiO_4^{4-}] with chl-*a* followed a similar trend where high chl-*a* values were observed at low nutrient concentrations (Fig. 14). The low nutrient values at the DCM may be attributed to the fact that nutrients are utilised by phytoplankton for metabolic activities. Below 150 to 200 m, an increase in nutrient levels at low chl-*a* which may be attributed to the decomposition of organic matter, causes regeneration of nutrients into the water column and these sink into deeper waters.

Discussion

Phytoplankton are the primary producers of the marine food web where they depend entirely on sunlight and carbon dioxide for photosynthetic activities and are therefore found in the euphotic zone (Williams and Follows, 2003). Nutrients are depleted in the euphotic zone as they are utilised by phytoplankton and cyanobacteria (Riegman, 1995), explaining a decrease in the level of nutrients in the upper water column, especially at the DCM. These nutrients are regenerated into the water column through respiration and decomposition of marine organisms, mostly in deeper waters (Riegman 1995; Harrison 1992; Levitus *et al*., 1993) as confirmed in the results presented here. Nitrite, NO_3^-, is an immediate product of nitrification from a microbial-mediated oxidation of NH_4^+ which is also consumed and reduced by primary producers and certain microorganisms for building organic molecules (Zakem *et al.,* 2018); which explains the values of NH_4^+ and NO_3^- being below detection limits.

The survey area exhibited an oligotrophic system characterised by low chl-*a* concentration. Usually the lowest concentration of chl-*a* in the EEZ of Mauritius is recorded in the months of April to June (Ramchandur *et al.,* 2017) which may explain the low chl-*a* values obtained during sampling in May. The SEC is the most dominant current passing through the Mascarene Plateau (New *et al.,* 2005; New *et al.,* 2007). The Indonesian Throughflow contains fresh water (Talley, 2011) which flows through the Mascarene Plateau bringing nutrients from the eastern part of the Indian Ocean (Schott and McCreary, 2001) and diverges across the Saya de Malha and Nazareth Banks through the channel (CTD station 434). The southern Indian Ocean usually receives nutrients from Circumpolar Deep Water (1500 to bottom) which is rich in nutrients (Panassa *et al.,* 2018).

The results showed that nutrient levels increased westward from the eastern part of the plateau. The decrease in temperature and high [SiO_4^{4-}] levels in the STSW region on the plateau may be attributed to the shallowness of the plateau, with the nutrients from the AIW being brought up to the STSW and SICW water masses. New *et al.* (2005) showed that this is partly due to the Ekman upwelling of the density surfaces on the northern side of the SEC. The current study showed higher concentration of nutrients in the northern part in comparison to the southern part. Furthermore, the Southwest Monsoon starts to develop during April to May where weak winds close to shore occur off Somalia causing the concentrations of phosphate and nitrate to increase towards the northern part of the Indian Ocean (Schott and McCreary, 2001). This might explain the low concentration of nutrients on the Nazareth Bank located in the southern part of the Mascarene Plateau.

In general, the Indian Ocean has higher nutrients levels that the Atlantic Ocean (Levitus *et al*., 1993). However, the southern Indian Ocean is poor in nutrients unlike the northern part which may be due to the absence of a general equatorial upwelling mechanism in the Indian Ocean (Garcia *et al.,* 2018; Gupta and Desa, 2001).

Conclusion

This study is the first, to the author's knowledge, conducted in the region of Saya de Malha and Nazareth Banks showing the distribution of nutrients in the water column. In general, the nutrient levels increase down the water column. The Saya de Malha Bank has a higher concentration of nutrients than the Nazareth Bank. Due to the shallowness of the plateau, the nutrient-rich AIW water mass in the deep layer brings nutrients to the SICW found in the upper layer on the plateau through upwelling. At the DCM, low nutrient levels were observed with an increase in the oxygen saturation greater than 94 %, indicating high primary productivity in that region. In order to obtain a better understanding of the change in productivity and the nutrient distribution throughout the year, more information on the water masses, seasonal variation of the nutrients, and other physicochemical parameters are required which could not be achieved in this study since data were collected only during one season.

Nevertheless, this study can be used a a baseline for other studies on the Mascarene Plateau.

Acknowledgments

The authors are thankful to the Food and Agriculture Organization (FAO) for funding the expedition in the Saya de Malha under the EAF-Nansen Programme on board the R/V Dr Fridtjof Nansen, Department of Continental Shelf, Maritime Zones Administration & Exploration of Mauritius for co-leading and coordinating the scientific expedition and the Mauritius Oceanography Institute (MOI) for participation in the expedition and their never-ending support towards the research study. The participants of the expedition: OA Bergstad, D Bissessur, N Reetoo, A Audit-Manna, A Nicolas, K Sauba, J Rama, P Coopen, Y Oozeeraully, M Soondur, R Bhagooli, S Seeboruth, L Caussy, S Ramah, J Harley, A Souffre, G Gendron, S Hollanda, R Melanie, D Kuyper, TM Ensrud and M Singh from the MOI are gratefully acknowledged.

References

Ardill JD (1986) Current status of fisheries in Mauritius. Food and Agriculture Organization, United Nations. 31 pp

Badal MR, Rughooputh SD, Rydberg L, Robinson IS, Pattiaratchi C (2009) Eddy formation around South West Mascarene Plateau (Indian Ocean) as evidenced by satellite 'global ocean colour' data. Western Indian Ocean Journal of Marine Science 8 (2): 139-145 [doi: 10.4314/wiojms.v8i2.56969]

Benson BB, Krause Jr D (1984) The concentration and isotopic fractionation of oxygen dissolved in freshwater and seawater in equilibrium with the atmosphere. Limnology and Oceanography 29 (3): 620-32 [doi: 10.4319/lo.1984.29.3.0620]

Betzler C, Lindhorst S, Lüdmann T, Reijmer JJ, Braga JC, Bialik OM, Reolid J, Eisermann JO, Emeis K, Rixen T, Bissessur D (2021) Current and sea level control the demise of shallow carbonate production on a tropical bank (Saya de Malha Bank, Indian Ocean). Geology 49 (12): 1431-1435 [doi: 10.1130/G49090.1]

Bhagooli R, Kaullysing D (2019) Seas of Mauritius–Chapter 12. In: Sheppard CCR (eds) World seas: an environmental evaluation, 2nd Edition, Volume II: The Indian Ocean to the Pacific. Elsevier, Academic Press. pp 253-277

Dharmendra D, Sólmundsson J (2005) Stock assessment of the offshore Mauritian banks using dynamic biomass models and analysis of length frequency of the Sky Emperor (*Lethrinus mahsena*). Fisheries Training Program, The United Nations University. 61 pp

Emery WJ (2001) Water types and water masses. Encyclopedia of ocean sciences 1 (6): 3179-3187

Fisher RL, Johnson GL, Heezen BC (1967) Mascarene Plateau, Western Indian Ocean. Geological Society of America Bulletin 78 (10): 1247-1266.

Garcia HE, Gordon LI (1992) Oxygen solubility in seawater: Better fitting equations. Limnology and Oceanography 37 (6): 1307-1312 [doi: 10.4319/lo.1992.37.6.1307]

Garcia CA, Baer SE, Garcia NS, Rauschenberg S, Twining BS, Lomas MW, Martiny AC (2018) Nutrient supply controls particulate elemental concentrations and ratios in the low latitude eastern Indian Ocean. Nature Communications 9 (1): 1-10

Grand MM, Measures CI, Hatta M, Hiscock WT, Landing WM, Morton PL, Buck CS, Barrett PM, Resing JA (2015) Dissolved Fe and Al in the upper 1000 m of the eastern Indian Ocean: A high-resolution transect along 95° E from the Antarctic margin to the Bay of Bengal. Global Biogeochemical Cycles 29 (3): 375-396 [doi: 10.1002/2014GB004898]

Grasshoff K, Johannsen H (1972) A new sensitive and direct method for the automatic determination of ammonia in sea water. ICES Journal of Marine Science 34 (3): 516-521

Grasshoff K, Kremling K, Ehrhardt M (2009) Methods of seawater analysis. John Wiley & Sons. 419 pp

Gupta RS, Rajagopal, MD, Qasim, SZ (1976) Relationship between dissolved oxygen and nutrients in the north-western Indian Ocean. pp 201-211

Gupta RS, Desa E (eds) (2001) The Indian Ocean: A perspective (Vol. 2). CRC Press. 906 pp

Harrison WG (1992) Regeneration of nutrients. In: Falkowski PG, Woodhead AD, Vivirito K (eds) Primary productivity and biogeochemical cycles in the sea. Environmental Science Research 43. Springer, Boston, MA. pp 385-407

Jena B, Sahu S, Avinash, K, Swain D (2013) Observation of oligotrophic gyre variability in the south Indian Ocean: environmental forcing and biological response. Deep Sea Research Part I: Oceanographic Research Papers 80: 1-10

Koroleff F (1972) Determination of reactive silicate. ICES Cooperative Research Report Series A 29: 87-90

Latasa M, Cabello AM, Morán XA, Massana R, Scharek R (2017) Distribution of phytoplankton groups within the deep chlorophyll maximum. Limnology and Oceanography 62 (2): 665-85

Levitus S, Conkright ME, Reid JL, Najjar RG, Mantyla A (1993) Distribution of nitrate, phosphate and silicate in the world oceans. Progress in Oceanography 31 (3): 245-273

Li G, Lin Q, Ni G, Shen P, Fan Y, Huang L, Tan Y (2012) Vertical patterns of early summer chlorophyll a concentration in the Indian Ocean with special reference to the variation of deep chlorophyll maximum. Journal of Marine Biology 20 (2) [doi:10.1155/2012/801248]

Morel A, Claustre H, Gentili B (2010) The most oligotrophic subtropical zones of the global ocean: similarities and differences in terms of chlorophyll and yellow substance. Biogeosciences 7 (10): 3139-3151 [doi: 10.5194/bg-7-3139-2010]

Munbodh M (2014) An EAF baseline report for the fisheries of shallow water demersal fish species of the Saya de Malha and Nazareth Banks of Mauritius. In: Koranteng KA, Vasconcellos MC, Satia BP (eds) Preparation of management plans for selected fisheries in Africa. FAO, Rome. pp 118-155

Murphy JA, Riley JP (1962) A modified single solution method for the determination of phosphate in natural waters. Analytica Chimica Acta 27: 31-36

New AL, Stansfield K, Smythe-Wright, Smeed, DA, Evans AJ, Alderson SG (2005) Physical and biochemical aspects of the flow across the Mascarene Plateau in the Indian Ocean. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 363 (1826): 151-168

New A, Alderson SG, Smeed DA, Stansfield KL (2007) On the circulation of water masses across the Mascarene Plateau in the South Indian Ocean. Deep Sea Research Part I: Oceanographic Research Papers 54 (1): 42-74 [doi:10.1016/j.dsr.2006.08.016]

Panassa E, Santana-Casiano JM, González-Dávila M, Hoppema M, Van Heuven SM, Völker, C, Wolf-Gladrow D, Hauck J (2018) Variability of nutrients and carbon dioxide in the Antarctic Intermediate Water between 1990 and 2014. Ocean Dynamics 68 (3): 295-308

Payet R (2005) Research, assessment and management on the Mascarene Plateau: a large marine ecosystem perspective. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 363 (1826): 295-307 [doi:10.1098/rsta.2004.1494]

Ragoonaden S, Babu VR, Sastry JS (1987) Physico-chemical characteristics and circulation of waters in the Mauritius-Seychelles Ridge zone, Southwest Indian Ocean. pp 184-191

Ramchandur V, Rughooputh SD, Boojhawon R, Motah BA (2017) Assessment of *chlorophyll-a* and sea surface temperature variability around the Mascarene Plateau, Nazareth Bank (Mauritius) using satellite data. Indian Journal of Fisheries 64 (4): 1-8

Resplandy L, Vialard J, Lévy M, Aumont O, Dandonneau Y (2009) Seasonal and intraseasonal biogeochemical variability in the thermocline ridge of the southern tropical Indian Ocean. Journal of Geophysical Research: Oceans 114 (C7) [doi: 10.1029/2008JC005246]

Riegman R (1995) Nutrient-related selection mechanisms in marine phytoplankton communities and the impact of eutrophication on the planktonic food web. Water Science and Technology 32 (4): 63-75

Sarmiento JL, Gruber N (2006) Ocean biogeochemical dynamics. Princeton University Press. 461 pp

Schlüter L, Henriksen P, Nielsen TG, Jakobsen HH (2011) Phytoplankton composition and biomass across the southern Indian Ocean. Deep Sea Research Part I: Oceanographic Research Papers 58 (5): 546-556

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

Stramma L, Lutjeharms JR (1997) The flow field of the subtropical gyre of the South Indian Ocean. Journal of Geophysical Research: Oceans 102 (C3): 5513-5530

Strickland JD, Parsons TR (1972) A practical handbook of seawater analysis. Fisheries Research Board of Canada, Ottawa, Ontario. 310 pp

Talley LD (2011) Descriptive physical oceanography: an introduction. Academic Press. 577 pp

Vortsepneva E (2008) Saya de Malha Bank – an invisible island in the Indian Ocean. Geomorfology, Oceanology, Biology. Report to the Lighthouse Foundation, Moscow, Russia. 42 pp [https://lighthouse-foundation.org/Binaries/Binary1070/Saya-de-Malha-report-final.pdf]

Williams RG, Follows MJ (2003) Physical transport of nutrients and the maintenance of biological production. Ocean biogeochemistry. Springer, Berlin, Heidelberg. pp 19-51

Zakem EJ, Al-Haj A, Church MJ, van Dijken G, Dutkiewicz S, Foster SQ, Fulweiler RW, Mills MM, Follow MJ (2018) Ecological control of nitrite in the upper ocean. Nature Communications 9 (1):1-13