

## Phytoplankton assemblages and pigments in the exclusive economic zone of Mauritius (Indian Ocean)

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Nutrient enrichment studies showed that both inorganic salts of nitrogen and phosphorus were limiting for phytoplankton from the surface waters. This coupled with conditions of high insolation prevailing at this time (Sept.-Oct.), severely curtailed phytoplankton growth in the surface waters leading to formation of a distinct subsurface chlorophyll maximum (SCM). In the vicinity of Agalega islands, the enhancement of phytoplankton biomass was associated with an upwelling process caused by the confluence of the westward flowing branch of the South Equatorial Current with the Seychelles-Mauritius Ridge. The inadequacy of processes such as vertical diffusion and nutrient regeneration in sustaining phytoplankton in surface waters highlights the importance of current-driven upwelling in transporting nutrients to the surface waters of the euphotic column within this region.

Information on marine phytoplankton from the Indian Ocean stems mainly from the observations<sup>1</sup> carried out during the International Indian Ocean Expedition (IIOE, 1960-1965). The first serious attempt to assess the biological productivity of this region was based on chl *a* data collected during the IIOE<sup>2</sup>. In a later study, available data on the Indian Ocean were integrated by Qasim<sup>3</sup> to project an overall picture of various aspects of phytoplankton productivity of this region. In the Central Indian Ocean (CIO) very few detailed investigations have been conducted ever since this pioneering work. Over this entire region, the sea constituting the Exclusive Economic Zone (EEZ) of Mauritius island have remained the least explored.

During a multidisciplinary oceanographic survey in September — October 1987, a comprehensive study of the biological features at the primary level of production in the EEZ of Mauritius was undertaken. The data collected have been discussed in relation to the physical and chemical features prevailing during the investigation.

### Materials and Methods

26 stations in the EEZ of Mauritius island were occupied during the present study (Fig. 1). At each station water samples from 5 discrete depths, corresponding to 100, 60, 30, 16 and 1% of the surface irradiance were collected using PVC Niskin water samplers. At few stations, sampling was extended beyond the 1% surface irradiance depth. Light penetration in the water column was established with an underwater Quantum Sensor (Licor, USA).

*Phytoplankton counts* — Phytoplankton samples were collected in 500 ml polythene bottles fixed with 1% Lugol's iodine solution and preserved in 3% buffered formaldehyde. The samples were allowed to settle for a few days and the supernatant solution was carefully decanted and discarded. Subsamples of sedimented material were later identified and enumerated in a Sedgwick Rafter Counting Chamber. One of the limitations of this technique is

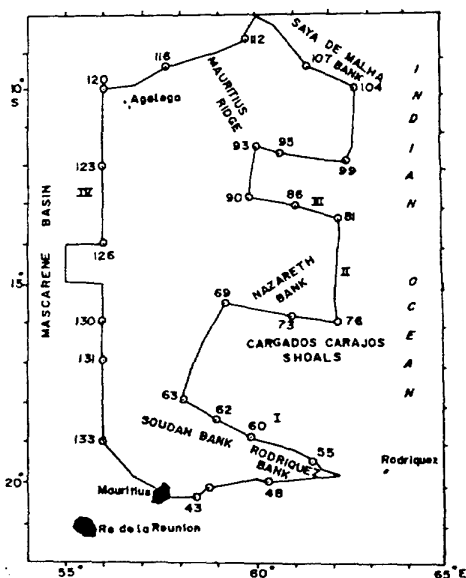


Fig. 1—Cruise track showing station positions and transects

that several organisms < 10 µm in size are not easily identifiable. It is also pertinent to note that picoplankton (operationally defined as organisms < 1 µm in diameter) tend to be excluded during the counting process on account of their small size. This measure of error may be particularly large in oligotrophic waters where these organisms are generally known to proliferate<sup>4</sup>.

**Chlorophyll a** — One to two litre samples in triplicate from each depth were filtered separately through GF/F glass fibre filters which were pretreated with a few drops of 1% magnesium carbonate suspension. The filters were immediately transferred to vials containing 10 ml solution of 90% acetone and extracted overnight under cold and dark conditions. Chl *a* and phaeopigments in the extracts were determined fluorometrically in a Turner Designs Fluorometer using standard methods<sup>5</sup>.

**Phytoplankton photosynthesis** — Phytoplankton carbon assimilation rates were measured in 125 ml water bottles using the <sup>14</sup>C method<sup>5</sup>. Samples were incubated in running seawater. Light in the bottles was attenuated using neutral density filters (Kahlsico, USA). At the end of the incubation period, which was generally 24 h, the water samples were filtered onto 0.45 µm cellulose membrane filters, exposed to conc. HCl fumes and the activity on them measured in a liquid scintillation counter (LKB, Sweden) using the channels ratio method for quench correction.

**Nutrient enrichment experiments** — These experiments were conducted at a few stations and were confined to seawater samples collected from just below the sea surface. Triplicate water samples were enriched with 1 µM salts of NaNO<sub>3</sub>, NaNO<sub>2</sub>, (NH<sub>4</sub>)<sub>2</sub>(SO<sub>4</sub>)<sub>2</sub>, NaH<sub>2</sub>PO<sub>4</sub>, Na<sub>2</sub>SiO<sub>3</sub> separately and in combination. Unenriched seawater was used as controls. Carbon assimilation in the samples was measured at the end of a 24 h incubation period using the <sup>14</sup>C technique<sup>5</sup>.

**Results**

**Distribution of chl *a*** — Surface chl *a* concentrations varied between 0.005 and 0.15 mg.m<sup>-3</sup> (Fig.2A). The lowest chl *a* concentrations (0.005 mg.m<sup>-3</sup>) were observed around Soudan Bank. Low values between 0.02 and 0.04 mg.m<sup>-3</sup> were recorded in the vicinity of Mauritius island increasing gradually northwards. Comparatively higher concentrations (0.06 to 0.09 mg.m<sup>-3</sup>) were recorded in the Nazareth Bank, Saya de Malha Bank and the Seychelles-Mauritius Ridge regions increasing markedly westwards in the vicinity

of Agalega islands. Surface chl *a* concentrations (0.10-0.15 mg.m<sup>-3</sup>) were much higher southwest of Agalega islands in the Mascarene basin.

Column chl *a* values integrated for the euphotic column varied between 1 and 13 mg.m<sup>-2</sup>. Very low values (1 to 2 mg.m<sup>-2</sup>) were observed north and northwest of Mauritius island, increasing gradually northwards (Fig.2B).

Vertical profiles of chl *a* at different stations show five kinds of depth-wise distribution patterns (Fig.3). Stations 43, 48, 55, 68, 73 and 76 showed low concentrations at the surface and highest at depths between 30 and 16% of surface irradiance (approx. between 25 and 50 m), forming a subsurface chl *a* maximum (SCM). Below this depth chl *a* concentrations decreased markedly again at 80 m (Fig.3A). In this area, the SCM chl *a* varied between

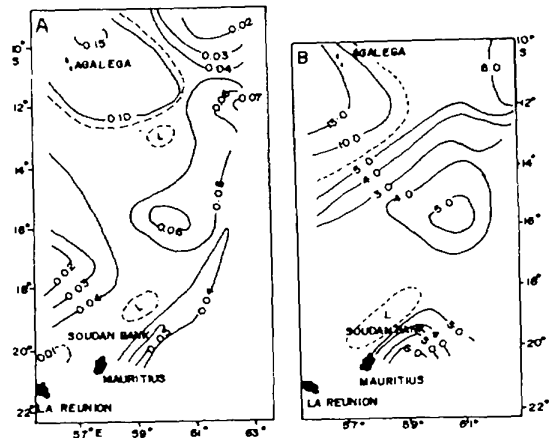


Fig. 2— Distribution of (A) surface chl *a* (mg.m<sup>-3</sup>) and (B) euphotic column chl *a* (mg.m<sup>-2</sup>)

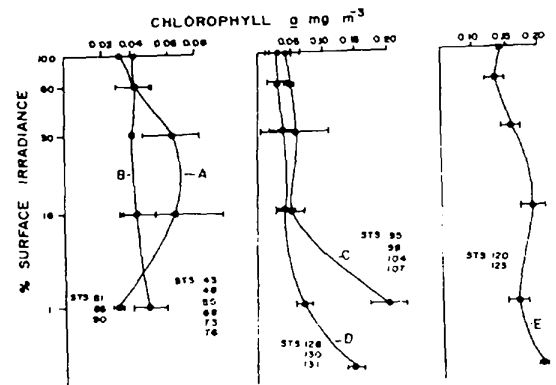


Fig. 3— Vertical profiles of chl *a* using pooled data from different stations (Horizontal lines represent error bars)

0.05 and  $0.15 \text{ mg.m}^{-3}$  which is about 2 to 5 times higher than the values observed at the surface. The area covered by sts. 81, 60 and 90 was characterised by absence of the SCM, where uniformly low values were recorded throughout the water column (Fig.3B). At sts. 95, 99, 104 and 107, the SCM was located at 80 m corresponding to 1% of the surface light intensity (Fig.3C). The SCM values of chl *a* varied between 0.16 and  $0.23 \text{ mg.m}^{-3}$  and were 4 to 23 times higher than the surface values. Stations 120 and 123 were characterised by the absence of the SCM (Fig.3D). In this case however, chl *a* concentrations were uniformly high throughout the euphotic column varying within a narrow margin of 0.14 to  $0.21 \text{ mg.m}^{-3}$ . An interesting feature observed in this region was the presence of chl *a* at depths below the euphotic zone. South of this region, at sts. 126, 130 and 131, the SCM was located below the euphotic zone at 100 m where chl *a* ranged from 0.14 to  $0.17 \text{ mg.m}^{-3}$  (Fig.3E).

Vertical distribution of chl *a* has been plotted along 4 transects (Fig.4). Along transect I (Fig.4A), chl *a* values were low throughout the water column, the lowest values being recorded in the Soudan Bank region at sts. 60, 62 and 63. Along the eastern meridional transect (transect II), a gradual increase in chl *a* values was observed northwards towards sts. 99 and 104 (Fig.4C). Along transect III (Fig.4B), an eastward increase in chl *a* was observed across the Seychelles-Mauritius Ridge. A conspicuous feature in the distribution of chl *a* values along this transect was the upward shoaling of isolines from below the euphotic zone upto 25 m at st. 90, spreading out between st. 123. A pocket of high chl *a* observed at approx. 30 m, was apparently in the region of the Seychelles-Mauritius Ridge. Along the southbound transect (transect IV), in the Mascarene Basin, high values were recorded in the first 100 m at sts. 120 and 123 (Fig.4D). Southwards, a decline in surface values was noticed leading consequently to a shift in the depth of the chl *a* maxima to 100 m from sts. 126 to 133.

*Phytoplankton assemblages* — 38 species of phytoplankton belonging to 4 different classes were identified. In order of dominance, Bacillariophyceae followed by Cyanophyceae, Pyrrophyceae (Dinophyceae) and Haptophyceae were the most abundant forms. Cell counts over the entire region varied widely between  $0.09 \times 10^3$  and  $6.8 \times 10^3$  counts.  $l^{-1}$  and were present in greater numbers in the subsurface waters. Bacillariophyceae members were dominated by solenoid diatoms. Cyanophytes were present at almost all the stations and consisted

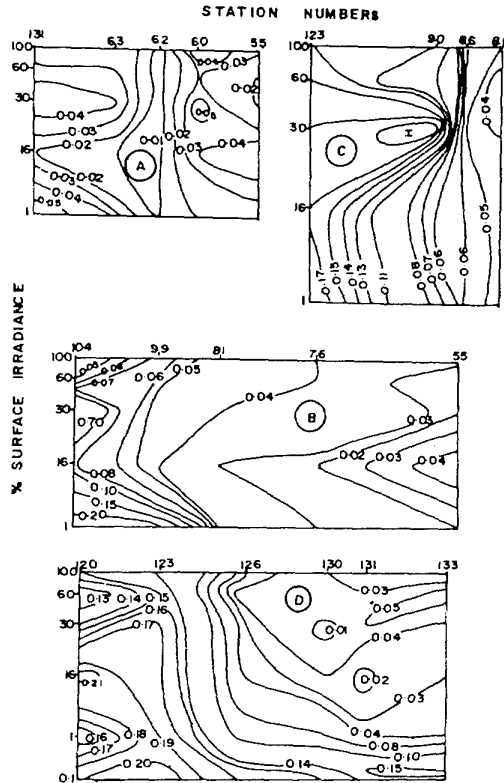


Fig. 4—Sectional distribution of chl *a* along transects I (A), III (B), II (C) and IV (D)

mainly of filamentous forms and clumps of unicellular coccoids.

Highest cell counts were recorded around Agaloga islands where the diatom *Rhizosolenia hebetata semispina* predominated. At sts. 63, 62, 60, 55 and 48 in the Soudan Bank and Rodriguez region, unicellular coccoid and filamentous blue-green algae were present.

Along the Seychelles-Mauritius Ridge (sts. 90, 93 and 95), diatoms were the dominant forms and were represented by *Nitzschia seriata*, *Coscinodiscus* sp., *Coscosira* sp., *Fragilaria* sp. and *Nitzschia* sp. Blue-green algal forms were represented by the colonial form *Aphanocapsa* sp., the epiphytoplanktonic form *Dermocarpa* sp. and filamentous forms belonging to the order Oscillatoriales.

The waters in the Saya de Malha Bank region (sts. 104, 107 and 112) were characterized by a mixed population of diatoms and dinoflagellates. The most common diatom was *Coscinodiscus* sp., *Navicula* sp., *Thalassiosira* sp. and *Melosira* sp. were present in

fewer numbers. The dinoflagellate population was represented by species of *Pouchetia* and *Gonyaulax*.

To the east and west of the Seychelles-Mauritius Ridge (sts. 76, 81, 99, 120, 123 and 126) the most commonly occurring form was the diatom *Rhizosolenia hebetata semispina*. The other diatoms observed were *Bacteriastrum cosmosum*, *B. varians*, *Cerataulina bergonii*, *Chaetoceros* sp., *Nitzschia* sp., *Rhizosolenia* sp. and *Thalassiosira* sp. The dinoflagellate population comprised of *Dinophysis* sp., whereas *Ceratocorys* sp. and *Dermocarpa* sp. and some filamentous forms comprised the blue-green algal population.

Towards the northeast of Mauritius in the Mascarene basin (sts. 130, 131 and 133), the dinoflagellate *Pouchetia* sp. and a few unidentified blue-green algae were observed.

**Photosynthetic rates** — Photosynthetic rates were in general low over most of the region ranging between 0.01 and 0.57 mg C.m.<sup>-3</sup>.h<sup>-1</sup>. The region around Agalega islands was comparatively more

productive, where photosynthetic rates varied between 0.12 and 0.57 mg C.m.<sup>-3</sup>.h<sup>-1</sup>. Elsewhere photosynthetic rates ranged from 0.01 to 0.09 mg C.m.<sup>-3</sup>.h<sup>-1</sup>. When normalized to unit chl *a*, photosynthetic rates were invariably higher at subsurface depths corresponding to 30 and 60% of the incident irradiance (Fig.5).

**Effect of nutrient enrichment on photosynthetic rates** — A marked increase in photosynthetic rates was observed in the samples enriched with nutrient salts (Fig.6). The enhancement was greatest in NH<sub>4</sub> and PO<sub>4</sub> and to a lesser extent in NO<sub>3</sub> and NO<sub>2</sub> enriched samples. In samples enriched with salts of SiO<sub>3</sub>, the enrichment was very marginal.

### Discussion

The present results show that a greater part of the seas comprising the EEZ of Mauritius are relatively less productive compared to adjacent coastal regions of the CIO, like the east coast of Africa and the west coast of Indonesia<sup>2</sup>. The chl *a* values recorded during

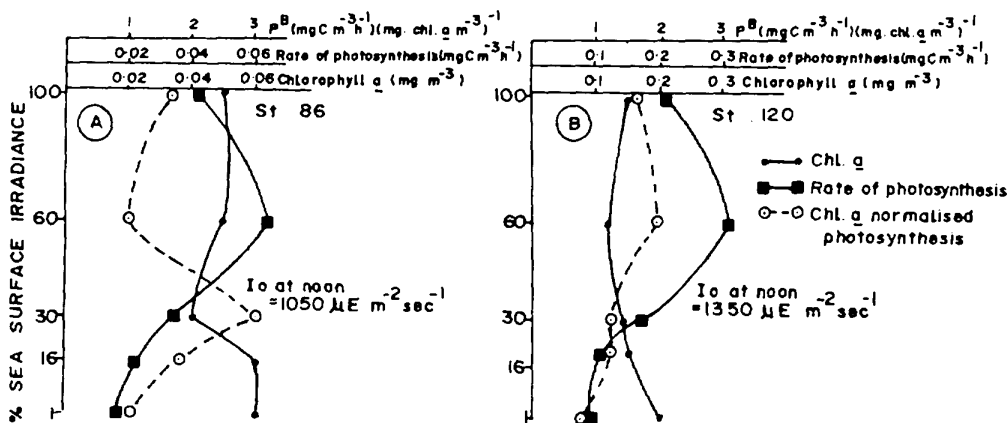


Fig. 5 — Vertical profiles of chl *a*, photosynthetic rates and chl *a* normalised photosynthetic rates in relation to sea surface irradiance (I<sub>0</sub>) at sts.86(A) and 120(B)

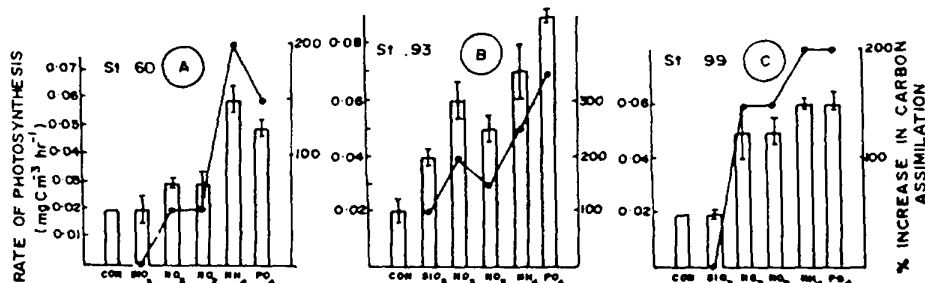


Fig. 6 — Variation in the rate of photosynthesis (bars) in unenriched seawater (control) and in seawater enriched with inorganic salts of silicate, nitrate, nitrite, ammonia and phosphate at sts.60(A), 93(B) and 99(C) (Vertical lines indicate deviation about the mean. Full continuous line indicates percentage increase in rates of carbon assimilation in enriched samples over control)

the present cruise are comparable to those recorded by Krey<sup>2</sup> and Qasim<sup>3</sup> and reflect the general paucity of phytoplankton in the CIO waters. Krey<sup>2</sup> attributed the low chl *a* concentrations in the CIO primarily to the strong thermal stratification persistent in this region.

Nutrient data collected during the present investigation do suggest a state of nutrient impoverishment in the euphotic column over a large area in the EEZ of Mauritius (unpublished data). At some stations blue-green algae proliferated. A sizeable number of marine cyanophytes are known to fix atmospheric nitrogen which give them a distinct ecological advantage over other phytoplankton for growth and survival in nutrient impoverished waters<sup>4,6,7</sup>.

A zone of elevated chl *a* concentrations was observed at sts. 120 and 123 in the leeward side of the Seychelles-Mauritius Ridge in the vicinity of Agalega islands. In this region the diatom, *Rhizosolenia hebatata semispina* was the dominant form, whilst *Rhizosolenia* sp. and *R. stolterfothii* were also present in appreciable numbers. The increase in the number of these diatoms can be attributed to the increased nutrient input into this area. *R. hebatata semispina* has been previously reported from nutrient rich waters of the southern Indian Ocean<sup>8</sup>. During the present investigation, an upward movement of the thermocline was observed to less than 100 m southwest of Agalega islands. Geostrophic flow calculations showed<sup>9</sup> that there was a strong (20 cm.sec<sup>-1</sup>) west bound current between 8° and 10°S lat. This westward flowing current on encountering the Seychelles-Mauritius Ridge appeared to produce a strong divergence on the leeward (west) side of the ridge resulting in upwelling of relatively nutrient rich waters. In earlier studies of this region, it was observed that the westerly flowing current was a branch of the South Equatorial Current and the divergence caused was an annual feature between June and September<sup>10,11</sup>. Further, apart from the Seychelles-Mauritius Ridge, the shallow bathymetry associated with the presence of Agalega islands could also be responsible for this unusual enrichment leading to enhanced concentrations of phytoplankton, particularly diatoms and pigments in this region. Since such high concentrations were not observed in the surrounding areas, this can possibly be classified as a localized phenomenon generated by topographic variation.

Vertical profiles of chl *a* in the euphotic column showed the presence of SCM at a number of stations (Fig.3). The presence of SCM is of considerable importance in tropical oligotrophic environments

where it is expected that prevailing conditions of high levels of insolation and low nutrient concentrations in the surface waters would readily favour its formation<sup>12</sup>. Nutrient concentrations recorded at most stations during this study (unpublished data) were much below the half-saturation constants reported for their uptake<sup>13-15</sup>. Similarly chl *a*-normalized photosynthesis vs light profiles (Fig.5) showed that phytoplankton in the surface waters were strongly photoinhibited. A similar observation was made by Saijo<sup>16</sup> based on *in situ* photosynthetic experiments along a longitudinal section in the Indian Ocean. Saijo<sup>16</sup> concluded that the formation of the SCM in this region was a result of excessive light which deteriorated plant pigments in the upper layers and growth and proliferation of shade-adapted phytoplankton in deeper waters.

The present results showed that chl *a* accounted for a sizeable percentage i.e. between 45 and 90% of the total estimated pigments (chl *a* + phaeopigments) in the SCM. Further, phytoplankton counts in the SCM were invariably high, arguing against the possibility of the SCM being formed of senescent cells sinking and accumulating in the region of the thermocline<sup>17</sup>.

In this study, the distribution of the SCM showed a fairly close degree of correspondence with that of nutrients. The vertical distribution of inorganic nitrate closely resembled that of chl *a* wherever a nitrate maxima was observed at or immediately below the SCM. Likewise, the distribution of chl *a* and inorganic phosphate also bore strong resemblance, an indication that phytoplankton in the water column were mainly dependent on nutrients diffusing across the thermocline.

In the Indian Ocean annual winter cooling, wind-driven upwelling and vertical diffusion of nutrients have been identified as the most important physical mechanisms for nutrient input into the euphotic zone<sup>18-21</sup>. In the CIO on account of the thermally stratified nature of the surface waters at this time of the year, the supply of nutrients to the euphotic zone is perhaps mainly through vertical eddy diffusion. However, it is evident that this process by itself is inadequate to meet the nutrient demands of phytoplankton especially in the top 50 m. Secondly the SCM by itself seems to be acting as a nutrient trap preventing the diffusion of nutrients into the surface waters.

This feature of nutrient limitation was evinced from enrichment experiments carried out on near surface populations of phytoplankton (Fig.6). The preferential uptake of NH<sub>4</sub> over NO<sub>3</sub> and NO<sub>2</sub> is explainable on the basis of energetics of their uptake. MacIssaac and Dugdale<sup>14</sup> have pointed out that NO<sub>3</sub>

is utilized considerably less effectively in oligotrophic waters than in eutrophic waters. They attribute this to the inability of phytoplankton which are not normally exposed to high concentrations of  $\text{NO}_3$  to utilize the ion effectively probably because of inadequate concentrations of nitrate reductase in their cells.  $\text{NH}_4$  is supplied to the euphotic zone of oligotrophic waters chiefly *via* nutrient regeneration during zooplankton excretion<sup>21</sup>. The enhanced rates of photosynthetic carbon assimilation observed in samples enriched with  $\text{NH}_3$  indicated that nutrient regeneration is also inadequate to sustain phytoplankton at the surface. The increase in photosynthetic rates in  $\text{PO}_4$  suggests that this nutrient was also limiting. In general, over large oceanic areas,  $\text{PO}_4$  is seldom a limiting nutrient for phytoplankton growth. However our results are in agreement with similar findings in the Central Pacific Ocean<sup>22</sup>, where it was noted that phosphate concentration reflected the productivity of the area. These findings are also in agreement with those in the North Pacific Ocean, where evidence from experiments involving nutrient uptake and alkaline phosphatase activity proved that phosphorus was almost equally involved with nitrogen in controlling the growth rates of phytoplankton<sup>23</sup>.

The waters which sustained the highest phytoplankton biomass were those in the vicinity of Agalega islands where a strong divergence resulting in upwelling of nutrient rich waters was noticed. These observations support earlier findings that phytoplankton in the CIO are in general nutrient impoverished. They also serve to highlight the importance of the process of current-driven upwelling over mechanism such as wind-driven upwelling in transporting nutrients into the surface layers of the euphotic zone in this area.

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