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Artículo Científico

Phytoplankton and its relationship with the physical-chemical variability in the marine ecosystem of the South Shetland Islands (Greenwich, Dee, Barrientos and Roberth), Antarctic during the austral summers 2023, 2024 and 2025

Fitoplancton y su relación con la variabilidad físico-química en el ecosistema marino de las Islas Shetland del Sur (Greenwich, Dee, Barrientos y Roberth), Antártida durante los veranos australes 2023, 2024, 2025

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Fitoplancton y su relación con la variabilidad físico-química en el ecosistema marino de las Islas Shetland del Sur (Greenwich, Dee, Barrientos y Roberth), Antártida durante los veranos australes 2023, 2024, 2025

ABSTRACT

The study, conducted between 2023, 2024, and 2025 in waters surrounding the Antarctic Peninsula and the South Shetland Islands, revealed marked temporal variability in the structure and composition of phytoplankton, closely related to local physical and chemical conditions. During the southern summers of 2023 and 2025, maximum chlorophyll concentrations were recorded, associated with an increase in nutrient availability and a decrease in salinity due to summer thawing, favoring the dominance of centric diatoms such as *Rhizosolenia imbricata*, *Corethron criophilum*, and *Thalassiosira rotula*. In contrast, during 2024, species with a lower contribution to total biomass (*Licmophora flabellata, Actinoptychus splendens, Surirella fastuosa*) prevailed. The positive correlations between chlorophyll-a, nitrate, and salinity with dominant species reflect a direct response of phytoplankton to nutrient availability and water column stability. These results are consistent with recent studies indicating an increase in primary productivity linked to sea ice retreat and greater surface layer stability. From an ecological perspective, the observed interannual variability highlights the sensitivity of Antarctic phytoplankton to large-scale climate forcings, confirming its key role in biogeochemical regulation and in the trophic base of the polar marine ecosystem.

Key words: *chlorophyll-a, diatoms, variability interanual, CCA, oceanic productivity*

RESUMEN

El estudio, desarrollado entre los años 2023, 2024 y 2025 en aguas circundantes a la Península Antártica y las islas Shetland del Sur, evidenció una marcada variabilidad temporal en la estructura y composición del fitoplancton, estrechamente relacionado con las condiciones físico-químicas locales. Durante los veranos australes de 2023 y 2025 se registraron máximas concentraciones de clorofila asociadas a un aumento en la disponibilidad de nutrientes y a una disminución de la salinidad producto del deshielo estival, favoreciendo la dominancia de diatomeas céntricas como *Rhizosolenia imbricata*, *Corethron criophilum* y *Thalassiosira rotula*. En contraste, durante el 2024 prevalecieron las especies (*Licmophora flabellata*, *Actinoptychus splendens*, *Surirella fastuosa*) con menor contribución a la biomasa total. Las correlaciones positivas entre clorofila-a, nitrato y salinidad con especies dominantes reflejan una respuesta directa del fitoplancton a la disponibilidad de nutrientes y a la estabilidad de la columna de agua. Estos resultados concuerdan con estudios recientes que indican un incremento de la productividad primaria vinculado al retroceso del hielo marino y a la mayor estabilidad de la capa superficial. Desde una perspectiva ecológica, la variabilidad interanual observada resalta la sensibilidad del fitoplancton antártico frente a forzantes climáticos de gran escala, confirmando su papel clave en la regulación biogeoquímica y en la base trófica del ecosistema marino polar.

Palabras claves: *clorofila-a, diatomeas, variabilidad interanual, ACC, productividad oceánica*

INTRODUCTIÓN

Antarctica has some of the harshest climatic conditions on our planet. The environmental climate significantly limits the diversity of living beings found in Antarctic ecosystems compared to those at lower latitudes (Camacho & Fernández, 2005).

The Antarctic ecosystem is of particularly scientific interest due to its unique characteristics, as it maintains high concentrations of inorganic nutrients, which are used by autotrophic phytoplankton, the basis of the food chain. In general, Antarctica has been considered a HNLC (High Nutrients Low Chlorophyll) zone because for most of the year phytoplankton is subjected to low temperature and darkness (Reeves et al., 2011). However, during the Antarctic summer, post-thaw conditions occur (Smith & Donalson, 2015) and a short season of high irradiance (Lee et al., 2022) that favors the photosynthetic activity of phytoplankton, which is mainly dominated by diatoms (Takao et al., 2014). These microalgae are a food source for more of 200 species of crustaceans, including krill (small crustaceans with a high protein content that, due to their abundance, can turn some marine areas in the Antarctic region reddish in color) (Torres et al., 2006).

Some studies describe the phytoplankton community and its successional variability in areas surrounding the South Shetland Islands in the summer of 1988 (Gómez, 1988). although it is not an Antarctic environment, they mention that microalgae such as Scenedesmus sp. have a direct relationship with DB05, removing 98.70% of it. They also point out that this microalgae was mainly used in industrial effluents and its application in an open system. Among the recorded algal species (certain Chrysophyceae), some have been shown to feed on bacteria (Bird & Kalff 1986); they are primarily autotrophic organisms and use heterotrophy to obtain nutrients.

Satellite images of ocean color can be used to calculate the concentration of chlorophyll present in phytoplankton and thus study the level of ocean productivity. The Patagonian Sea is a highly productive marine environment, with phytoplankton abundance values approximately three times higher than the average recorded in the rest of the oceans. Phytoplankton is not distributed evenly but is more concentrated in limited regions associated with ocean fronts (Piola & Falabella 2009).

Burgos (1998) mentions that the surface waters of the Branfield Strait were less oxygenated than those reported in previous studies, as result of the El Niño 97-98 warm event that weakened the southern trade winds.

Cháux (2001), in his study, determined high concentrations of dissolved oxygen in Guayaquil Cove, Greenwich Island. Valencia (1998) describes the results of dissolved and dispersed hydrocarbons, dissolved oxygen, nutrients, and microbiology found in Chile Bay during the southern summers of 1995 and 1998, without recording any negative effects from anthropogenic activities. The others study (Ye., S. Z. Zhagan., T. Vihma. M. Jiang, Ch. Xie, L. Yu, W.O Smith., 2025), the Northern Antártic Peninsula (NAP) region had substantially elevated phytoplankton biomass, with surface chlorophyll-a concentrations that reached the greatest level during 2001–2023.

The purpose of the study is to determine changes in phytoplankton species communities and their relationship with physical-chemical variables in the surface layer during the southern summers of February 2023, January-February 2024, and February 2025 in the Antarctic ecosystem in the South Shetland Islands, Antarctica.

MATERIAL AND METHODS

Study area

A total of 13 stations were monitored, distributed around the islands of Greenwich, Barrientos, Dee and Robert (South Shetland), in the Antarctic region (Figure 1). This information was collected during

Ecuadorian scientific expeditions planned by the Navy's Oceanographic and Antarctic Institute during expeditions XXVI, XXVII and XXVIII, which took place from 24 February to 3 March 2023, 15 January to 5 February 2024 and 2 to 11 February 2025.

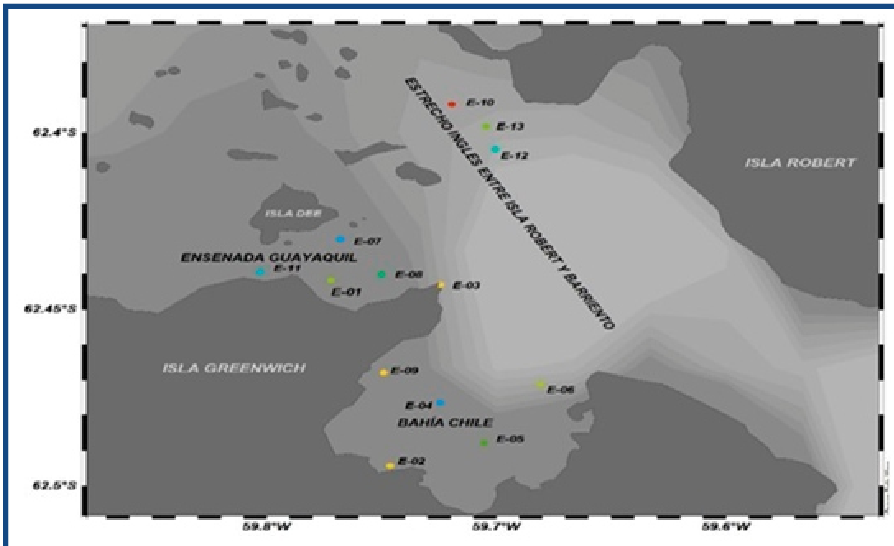

Figure 1. Location of sampling stations off Greenwich, Roberth, Dee, and Barrientos Islands during the southern summers of 2023, 2024, and 2025.

During field sampling, surface water samples were collected in situ using a Niskin bottle and YSI Model 85 multiparameter equipment to measure SST, salinity, dissolved oxygen, and pH. Surface water samples were also collected for nutrient analysis (nitrates, nitrites and phosphates) at the Pedro Vicente Maldonado scientific station laboratory, as well as for chlorophyll-a analysis.

Subsequently, with the help of the boat, surface trawls were carried out at a speed of 2 knots for 5 minutes, using a simple conical cylinder net with a 30 cm diameter mouth and a 50 µm mesh opening to collect phytoplankton samples. The phytoplankton samples were fixed in a 2% formaldehyde solution, previously neutralised with sodium tetraborate, for subsequent identification at the Pedro Vicente Maldonado station and at the INOCAR Marine Biology and Chemistry Laboratory.

For nutrient analysis, the method described in Strickland & Parsons (1972) was applied, using a spectrophotometer, and micronutrient units were expressed in µmol/L. Chlorophyll analyses were performed following the method described in the SCOR UNESCO Manual, Working Group 17, (1966), using Turner Design fluorometer equipment, and chlorophyll units were expressed in mg/m^3.

For the analysis of the samples, these were homogenised and three aliquots were obtained, following the methodology of Semina (1963), using a microscope slide and a 20 x 20 mm coverslip. Taxonomic

identification was carried out using the specialised taxonomic keys of (Cupp, 1940, Jiménez 1983, Pesantes 1983, Zambrano 1983, Moreno et al., 1996, Hansonn, L.A & H. Hakansson. 1992, Van de Vijver. B & L. Beyens 1997, and Mrozinska, et al., 1998).
The qualitative results for phytoplankton were expressed in cells/m^3.

Data analysis

Differences between hydrographic variables (temperature, salinity, dissolved oxygen, nitrite, nitrate, phosphate and chlorophyll a) were evaluated and a non-parametric analysis of variance (Kruskal Wallis) after verifying non-compliance with normality (Shapiro Wilk) and Levene's homoscedasticity (Sheskin, 2003); (Komárek, 1999). Subsequently, surface distribution maps of the environmental variables were produced for each expedition using the Ocean Data View (ODV) programme.

Canonical correspondence analysis (CCA) (Ter Braak, 1986) was used to establish the relationship between phytoplankton species and hydrographic variables.

Similarly, to establish possible differences between the community structure of the three expeditions, Similarity Analysis (ANOSIM) was performed, expressed in Non-parametric Multidimensional Scaling (NMDS) according to Clarke & Warwick (2001).

The community index (Importance Value Index) was used for each expedition to establish the important phytoplankton species using ecological parameters such as abundance, frequency and density of each species recorded in each expedition.

All analyses were performed using PAST UIO ver 5.2 software (Hammer & Harper, 2001).

RESULTS

Oceanographic conditions of physical-chemical variables during the southern summers of February 2023, January-February 2024, and February 2025.

The SST in the Antarctic region located between the Greenwich, Dee, Robert and Barrientos islands during the southern summer of 2023 presented values that fluctuated between 0.6° and 4.6°C, which were higher than the minimum and maximum ranges observed (1.3°- 2.2°C) and (1.1 - 1.8°C) corresponding to the southern summers of 2024 and 2025, respectively (Figure 2a).

Surface salinity in the summer of 2023 ranged between 22.9 and 25.1 ups salinity, which was distributed uniformly throughout the study area.

While salinity in mid-January 2024 showed high salinity characteristics at some stations with values above 35.9 ups located near Robert Island and Greenwich Island, as the sampling days passed, salinity began to decrease, with values reaching 20.7 ups in Chile Bay and Guayaquil

Cove. The minimum salinity value of 20.7 ups recorded was lower than those observed in the southern summer of 2023. This low salinity value is mainly related to the contribution of fresh water from melting ice observed during the southern summer of 2024 (Figure 2b). Meanwhile, the salinity values recorded in the southern summer of 2025 ranged between 25.7 and 26.1 ups, which were widely distributed in the region between Greenwich, Dee, Barrientos and Robert Islands. The minimum salinity value was higher than that recorded in 2023.

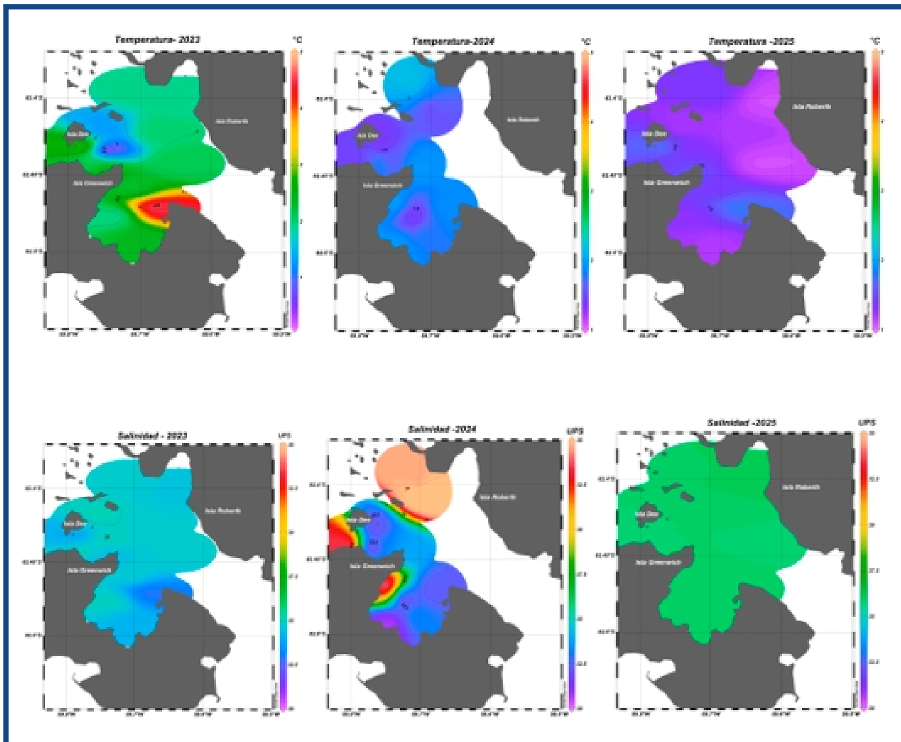

Figure 2. Distribution of variables a) Sea Surface Temperature, b) Surface salinity in the South Shetland Islands during the southern summers of 2023, 2024, and 2025.

The surface seawater in the study area was oxygenated during the 2024 period, with maximum values of 9.34 ml/L and minimum values of 8.32 ml/L. These dissolved oxygen values were higher than those recorded during the 2023 austral summers (8.31–7.30 ml/L) and like those recorded in 2025 (9.20–8.50 ml/L) for surface dissolved oxygen (Figure 3a).

The maximum and minimum pH values during the southern summers of 2023, 2024, and 2025 were between 8.76-7.40, 8.28-7.88, and 8.81-7.91, respectively, in the surface layer, which is normally considered alkaline water that favors phytoplankton biota, which requires a healthy environment for the development and growth of its siliceous structures. However, there is a global trend of a slight decrease in hydrogen potential in some marine ecosystems, and in the period under study, there is a slightly alkaline minimum value of 7. 40 pH recorded in the southern summer of 2023, which increased for the summers of 2024 and 2025 with minimum pH values of 7.88 and 7.91, respectively (Figure 3b).

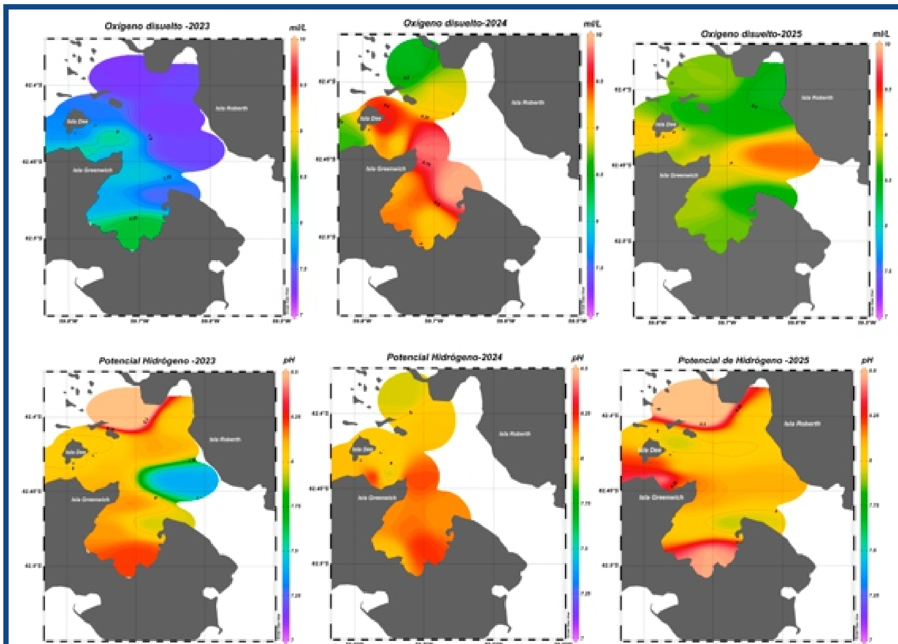

Figure 3. Distribution of variables a) Dissolved oxygen and b) Surface hydrogen potential in the South Shetland Islands during the southern summers of 2023, 2024, and 2025.

In the Antarctic marine ecosystem, nitrites were scarce during the southern summers of 2023 and 2025, reaching maximum nitrite concentrations of 0.152 and 1.14 umol/L, respectively. The temporal patterns of low nitrate concentrations were similar, possibly associated with consumption by the dominant phytoplankton species recorded during 2023 and 2025. Nitrates play a vital role in the Antarctic ecosystem, as they are one of the important forms that can be used by phytoplankton.

During the southern summer of 2024, nitrite values were higher, reaching values between 0.14-3.50 umol/L, and nitrates registered values between 9.7-79.0 umol/L (Figure 4 a-b).

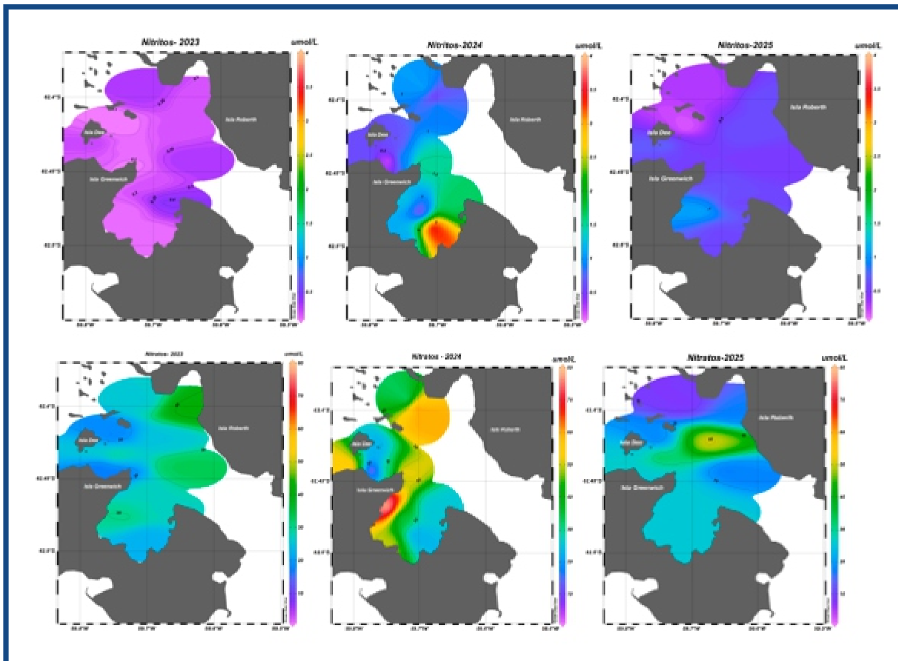

Figure 4. Surface distribution of variables a) Nitrites, b) Surface nitrates in the South Shetland Islands during the southern summers of 2023, 2024, and 2025.

Phosphates were mainly consumed by phytoplankton during the southern summer of 2023, as the lowest concentrations were recorded compared to 2024 and 2025. Phosphates are produced from the decomposition of organic matter, which is an important source of phosphorus for phytoplankton.

The maximum phosphate value recorded in 2023 was 3.0 umol/L at the surface level, followed by 23.8 umol/L and 27.77 umol/L reported for 2024 and 2025, respectively (Figure 5).

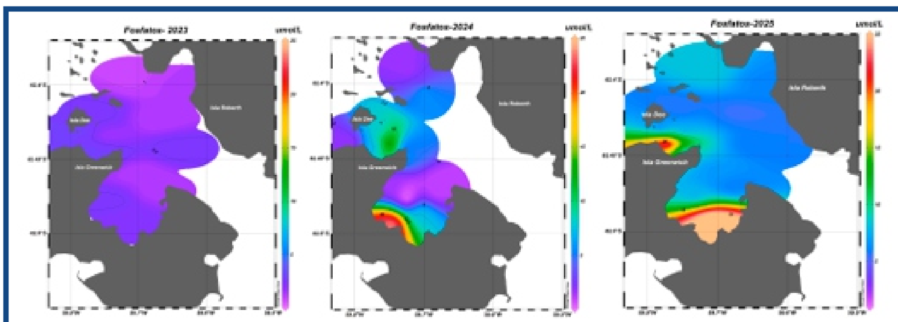

Figure 5. Distribution of the surface phosphate variable in the South Shetland Islands during the southern summers of 2023, 2024, and 2025.

The maximum concentrations of chlorophyll-a in the surface layer were recorded in the southern summer of 2025, with high chlorophyll-a values with cores between 12.2 mg/m^3 and 6.02 mg/m^3 located at the entrance to Chile Bay and a second core recorded between Greenwich and Dee Islands with values of 10 mg/m^3. Similar patterns with high chlorophyll-a concentrations were observed in the southern summer of 2023 in Chile Bay, with values fluctuating between 9.30 and 8.20 mg/m^3, and a second core with values of 6.8 mg/m^3 was observed in Guayaquil Bay (Figure 6). Low chlorophyll-a productivity was recorded during 2024 in the surface layer, with values ranging between 0.08 and 1.04 mg/m^3. This low chlorophyll-a productivity may be associated with changes in community structure and the dominance of phytoplankton species.

One of the aspects to note during the southern summer of 2024 was the presence of sea ice around the Greenwich, Dee, and Barrientos islands. Consequently, lower solar radiation influences lower surface chlorophyll-a concentrations (Figure 6).

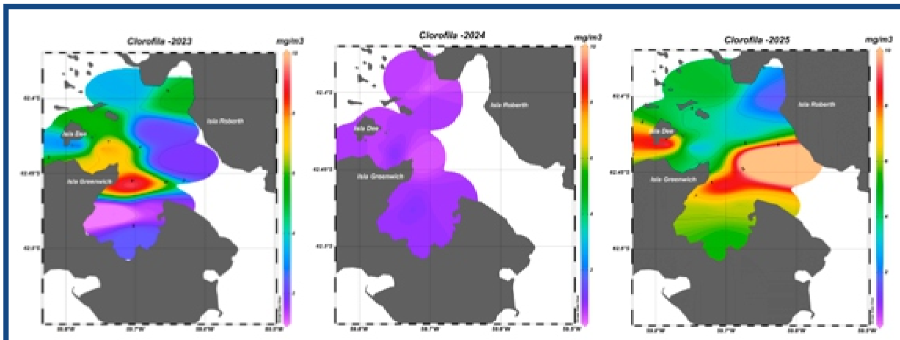

Figure 6. Distribution of surface chlorophyll-a in the South Shetland Islands during the southern summers of 2023, 2024, and 2025.

During the expedition carried out in 2023, the first component determined a positive correlation between salinity and nitrite with *Coscinodiscus concinus*, inversely related to phosphate, ammonium, and temperature. These physical-chemical variables were associated with *Eucampia zoodiacus, Rhizosolenia acuminata, and Thalassiosira rotula*. In the second component, there was an inverse association between *Thalassiosira subtilis* and chlorophyll-a and phytoplankton abundance, as well as pH. There was a positive correlation between *Licmophora flabellata* and *Chaetoceros curvisetus* with chlorophyll-a and pH (Figure 7).

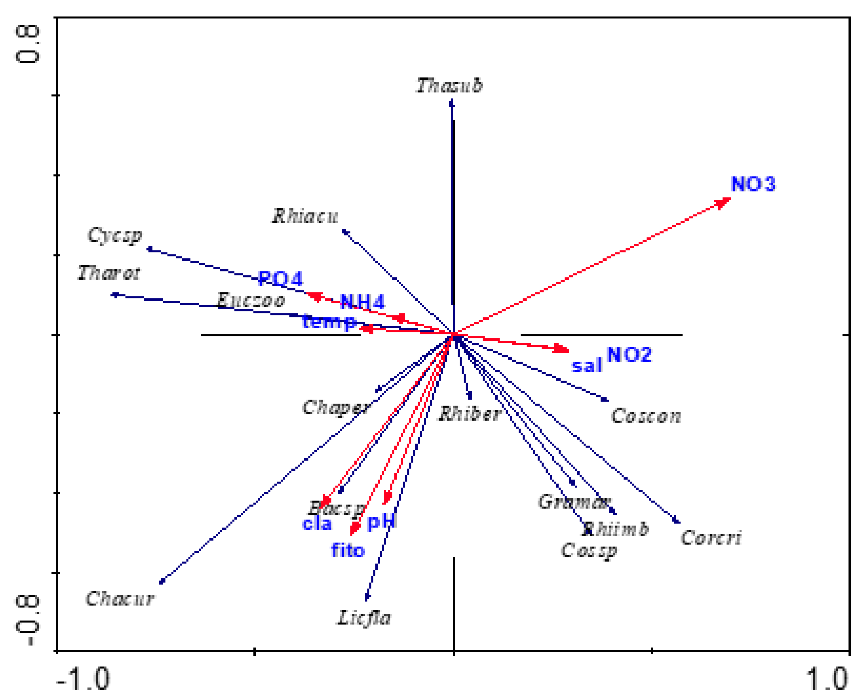

Figure 7. Orthogonal projection of the first two components of the phytoplankton redundancy analysis from the 2023 Antarctic expedition. Where: temp: temperature, sal: salinity, NO2: nitrite, NO3: phosphate, NH4: ammonium, PO4: phosphate, Chla: chlorophyll-a, phyto: phytoplankton Cycsp: Cyclotella sp., Euczoo: *Eucampia zoodiacus*, Tharot: *Thalassiosira rotula*, Rhiacu: *Rhizosolenia acuminata*, Chaper: *Chaetoceros peruvianus*, Rhiber: *Rhizosolenia bergonii*, Coscon*: Coscinodicus concinnus*, Gramar: *Grammatophora marina*, Rhiimb: *Rhizosolenia imbricata*, Cossp*: Coscinodiscus sp,* Corri:*Corethron criophilum*.

Canonical correspondence analysis (CCA) showed that many phytoplankton species during the southern summer of 2024, *Coscinodiscus excentricus* and *Actinoptychus splendes*, are related to chlorophyll-a, and these species are not correlated with the variables temperature, nitrites, nitrates, and phosphates (Figure 8).
Meanwhile, *Licmnophora flabellata* and *Odontella pulchella*, despite representing 84% and 68% respectively in the ecosystem importance index, do not correlate with environmental variables due to their wide distribution in the marine ecosystem.

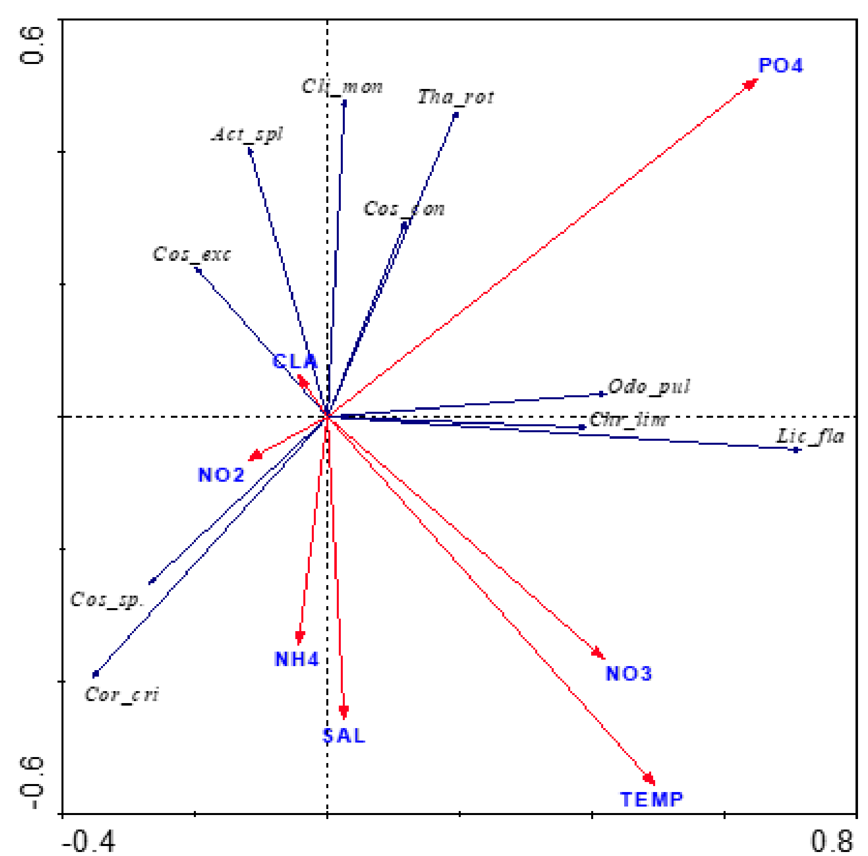

Figure 8. Orthogonal projection of the first two components of the principal component analysis of phytoplankton in the 2024 Antarctic expedition. Where: temp: temperature, sal: salinity, NO2: nitrite, NO3: phosphate, NH4: ammonium, PO4: phosphate, Chla: chlorophyll-a, phyto: phytoplankton. Cossp*: Coscinodiscus sp,* Corcri:*Corethron criophilum,* Cosexc*: Coscinodicus excentricus*, Actspl: *Actinoptychus splendes Climon*: *Climacosphaenia monoligera;* Tharot: *Thalassiosira rotula*, Coscon: *Coscinodiscus concentricus*; Odopul: *Odontella pulchella* Chrlim: *Chrococcus limneticus*.

The Canonical correspondence analysis (CCA) during the 2025 expedition showed a correlation with ambient species of 0.92 in the first component and 0.76 in the second. With a cumulative variance of 70.1% in the first two components. In component 1, a significant positive correlation was detected between nitrate, nitrite and salinity with *Coscinodiscus concinus* and a negative correlation with phosphate and temperature correlated with *Cylcotella sp. Thalassiosita rotula* and *Eucampia zodiacus*. In component 2, a negative correlation was detected between *Thalassiosira subtilis* and chlorophyll, pH, and *Licmophora flabellata* (Figure 9).

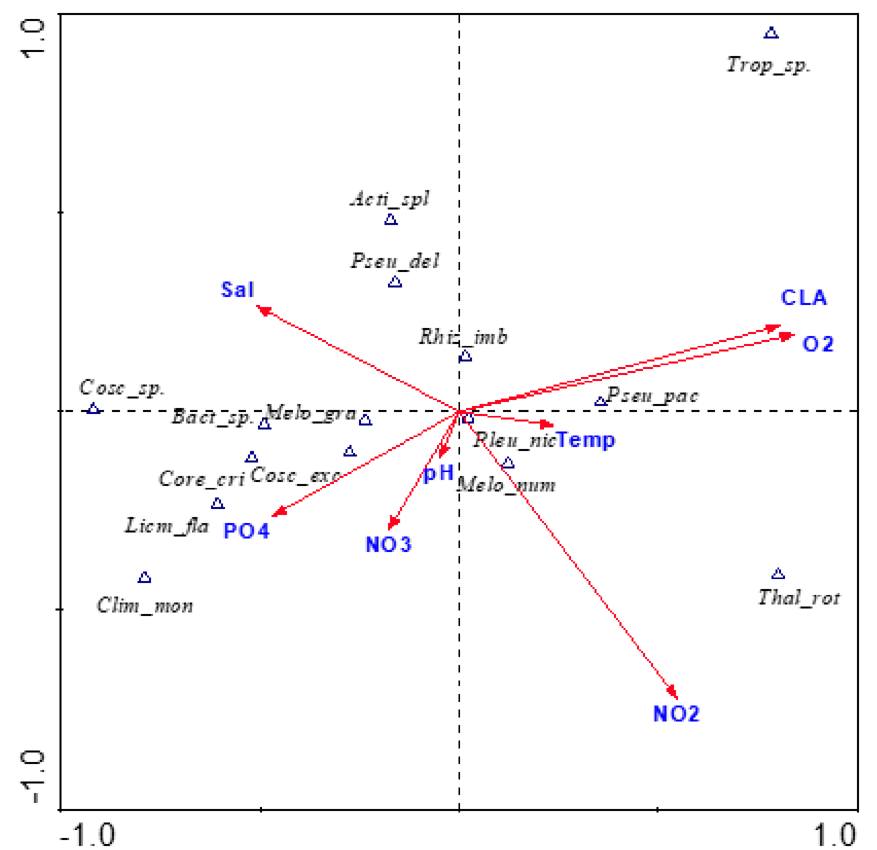

Figure 9. Orthogonal projection of the first components of the principal component analysis of phytoplankton in the 2025 Antarctic expedition. Where: temp: temperature, sal: salinity, NO2: nitrite, NO3: nitrate, PO4: phosphate, Chla: chlorophyll-a, Cossp*: Coscinodiscus sp,* Corcri:*Corethron criophilum,* Cosexc*: Coscinodicus excentricus*, Actspl: *Actinoptychus splendes* Rhiimb: *Rhizosolenia imbricata*,Climon: *Climacosphaenia monoligera, Licmfla: Licmnophora flabellata, Pseu del: Pseudo-nitzschia delicatissima,* Tharot: *Thalassiosira rotula*,Ple nic: *Pleurosigma nicobaricum, Melo num: Melosira granulata*

Similarity analysis (ANOSIM) showed structural differences ($R=0.881$; $p<0.001$). Structural homogeneity was greatest in 2023, while in 2024 and 2025 there was greater data dispersion due to changes in the phytoplankton community structure (Figure 10).

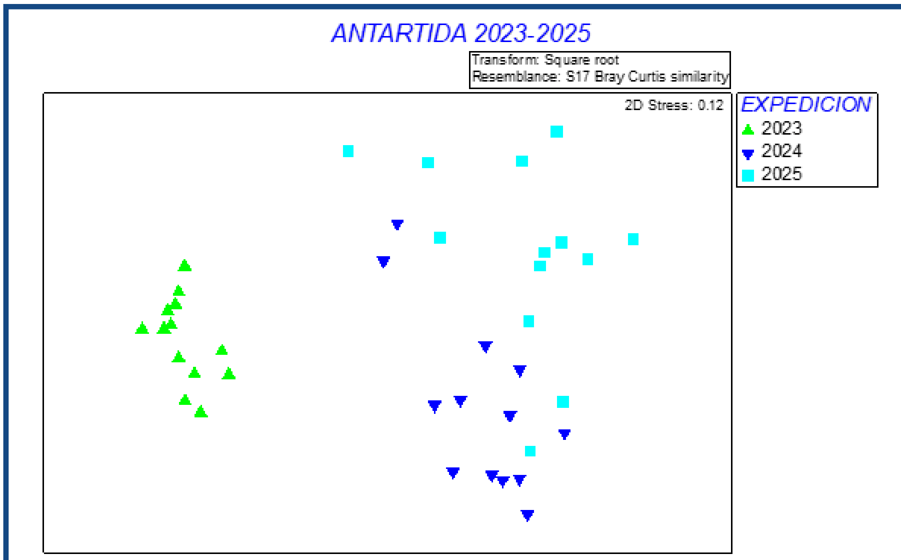

Figure 10. MDS diagram of the phytoplankton community structure in the Antarctic expeditions from 2023 to 2025.

According to the community structure of phytoplankton species on the Antarctic Peninsula, there is variation in species dominance, mainly among species evaluated using the Importance Value Index for each year (Table I).

In the southern summer of 2023, the species with the highest importance value were: *Rhizosolenia imbricata, Corethron criophilum, Thalassiosira rotula, Rh. bergonii, Licmnophora flabellata, Rhizosolenia acuminata, Cyclotella sp*, and *Thalassiosira subtilis. Chaetoceros curvisetus* and *Ch. peruvianus* were of lesser importance. This important composition in the phytoplankton community contributed to high marine fertility, due to maximum concentrations of chlorophyll-a, associated with the availability of nutrients.

During the southern summer of 2024, the species of greatest importance were *Licmnophora flabellata, Surirella fastuosa, Thalassiosira rotula, Coscinodiscus concinnus, Climacosphaenia monoligera, Chrococcus limneticus, Corethron criophilum, Thalassiosira subtilis* and *Odontella pulchella. Grammatophora marina* and *Surirella fastuosa* were of lesser importance. The association of these species did not favor phytoplankton concentrations.

Compared to the southern summer of 2025, the most important species were: *Pseudo-nitzschia pacifica, Licmnophora flabellata, Actinoptychus splendes, Thalassiosira rotula, Melosira granulata, Coscinodiscus excentricus, Pseudo-nitzschia delicatissima,* and *Rhizosolenia imbricata*. Some of these phytoplankton species had similar importance to those observed in the southern summer of 2024 (Figure 10).

Table I. Importance Value Index (IVI) of phytoplankton species recorded in the marine environment of the South Shetland Islands during the Antarctic expeditions of 2023, 2024 and 2025.

Species	Expedition 2023	Expedition 2024	Expedition 2025
Rhizosolenia imbricata	52.8 IVI	7.9 IVI	*20.9* IVI
Corethron criophilum	46.8 IVI	29.0 IVI	31.0 IVI
Thalassiosira rotula	44.7 IVI	38.6 IVI	33.4 IVI
Rhizosolenia bergonii	38.2 IVI	--	5.2 IVI
Licmnophora flabellata	34.8 IVI	70.6 IVI	45.9 IVI
Rhizosolenia acuminata	33.4 IVI	--	--
Cyclotella sp	32.9 IVI	10.3 IVI	--
Thalassiosira subtilis	31.5 IVI	27.0 IVI	13.1 IVI
Chaetoceros curvisetus	26.4 IVI	2.5 IVI	--
Chaetoceros peruvianus	24.4 IVI	--	--
Surirella fastuosa	5.13 IVI	39.6 IVI	7.7 IVI
Coscinodiscus concinnus	31.3 IVI	33.3 IVI	13.5 IVI
Coscinodiscus excentricus	15.4 IVI	28.8 IVI	32.0 IVI
Climacosphaenia monoligera	7.66 IVI	31.0 IVI	23.3 IVI
Odontella pulchella	12.8 IVI	25.8 IVI	16.6 IVI
Grammatophora marina	31.5 IVI	20.9 IVI	15.4 IVI
Chrococcus limneticus	--	29.3 IVI	--
Surirella fastuosa	5.1 IVI	20.7 IVI	7.70 IVI
Actinoptychus splendes	5.1 IVI	39.6 IVI	35.6 IVI
Pseudo-nitzschia pacífica	--	--	52.9 IVI
Pseudo-nitzschia delicatissima	7.6 IVI	--	26.4 IVI
Melosira granulata	--	--	34.7 IVI

DISCUSSION

During austral summer the waters surrounding the Antarctic Peninsula and the South Shetland Islands are very rich in phytoplankton production. Sánchez (2007) points out that the high abundance of phytoplankton is due particularly to areas of contact between sea ice and the open sea, where there is an upwelling of warmer, nutrient-rich waters. SST values on Greenwich Island showed no differences during the southern summers of 2024 and 2025. However, differences were observed in the patterns of chlorophyll-a concentrations and nutrients (nitrates and phosphates) recorded in 2023 and 2025.

During the summer of 2023, there was a positive correlation between the species *Licmophora flabellata* and *Chaetoceros curvisetus* with chlorophyll-a and pH, which is interpreted as meaning that environmental conditions were favorable for biological productivity. Ferreira et al., (2024) mention the importance of environmental conditions in shaping phytoplankton dynamics, as evidenced in the Bransfield Strait, due to its high variability in bloom phenology and phytoplankton biomass, which contributes to high spatial and temporal variability. The presence of diatoms reaffirms their importance in this ecosystem, with chlorophyll-a concentrations of 12.2 mg/m^3 in 2025 near Robert Island. Cazarin-Baldoni, (2025) point out in their study similar chlorophyll values (12.02 mg.m−3) that were recorded in 2018 in the Garleche Strait, associated with the dominance of diatoms.

Ferreira et al. (2024) in their study of 25 years of satellite data (1998-2022), presented evidence that phytoplankton biomass and bloom phenology in the Western Antarctic Peninsula are changing significantly in response to anthropogenic climate change. This is why, in the southern summers of 2023 and 2025, maximum concentrations of chlorophyll associated with nutrient availability were observed in Guayaquil Cove, Chile Bay, Antarctica. Another factor mentioned Ferreira et al., (2024) that could be contributing is the long-term decline in sea ice, which was identified as the main driver of phytoplankton growth in early spring and autumn. Comparing with the southern summers of the present study, it was determined that there is a large contribution of fresh water to the marine ecosystem due to ice melt, which favors low salinity concentrations, registering values of 20.71 ups observed in the southern summer of 2024, These changes in environmental conditions over a short period of time contribute to the dynamics and community structure in the composition of phytoplankton diatom species.

Some studies suggested that this increase in biomass was a consequence of a more stable mixed upper layer during the austral summers due to meltwater resulting from climate-induced sea ice decline and glacier retreat (Montes-Hugo et al., 2009).

In general, Antarctica has been considered an HNLC (High Nutrients Low Chlorophyll-a) zone because phytoplankton is subjected to low temperatures and darkness for most of the year (Reeves et al., 2001). However, during the southern summers of 2023 and 2025, favourable environmental conditions with high chlorophyll-a concentrations occurred due to the Importance Value Index of dominant phytoplankton species (Smith & Donalson, 2015). The abundance of centric diatoms is mainly due to the thawing of ice and associated with the presence of a short season of irradiance. Lee et al., (2022) point out that photosynthetic activity favors phytoplankton, mainly diatoms (Takao et al., 2014). This leads to the conclusion that the abundance of phytoplankton species changes in time and space on short scales during the period (2023-2025). This is in addition to the large-scale physical processes associated with climate adjustments that manifest themselves as ecological responses on smaller scales (Thomalla et al., 2023). It is therefore essential to interpret and compare the variability in the ecosystem in the South Shetland Islands that occurred in 2023. The species of greatest importance were *Rhizosolenia imbricata*, *Corethron criophilum* and *Thalassiosira rotula*, diatoms that contributed to high marine fertility. However, these patterns change over time, and during the 2024 austral summer, *Licmnophora flabellata*, *Actinoptychus splendes*, and *Surirella fastuosa* were recorded, whose phenotypic characteristics do not contribute to the generation of high concentrations of chlorophyll-a.

Some phytoplankton species in the Antarctic ecosystem have the ability of withstand low temperatures (Fahl & Kattner, 1993) due to the high presence of fatty acids, as well as the ability to generate auxospores that are activated during thawing (Reeves et al., 2011).

During the Antarctic summer of 2025, the species of greatest ecological importance were *Pseudo-nitzschia pacifica*, *Licmnophora flabellata*, *Actinoptychus splendes, Thalassiosira rotula*, two of which were similar that those observed in the summer of 2024 and one of which was similar that those observed in 2023. Compared with studies conducted by Sánchez et al. (2013) in the Bransfield Strait in the summer of 2013, this confirms the presence of the genera Pseudo-nitzschia and Thalassiosira.

The presence of common diatoms noted between 2023 and 2025 coincides with research carried out in a study by Torres et al. (2013). In general, pennate diatoms such as Pseudonitzschia sp. and Fragillariopsis sp. have been considered dominant (Sagiammo et al., 2021). However, in the present study, centric diatoms such as *Corethron criophyllum*, *Thalassiosira rotula* and *Coscinodiscus concinum*, and the pennate *Licmophora flabellata* and *Climacosphaenia moniligera* were considered dominant. According to the study by Kawaguchi et al. (2014), these species have been identified as important species in the trophic web that sustains krill. In this regard, Schofield et al. (2024) point out that diatoms are responsible for the food quality of this zooplankton community, and studies should focus on interannual variability.

From an ecological and climatic perspective, the results suggest that the variations observed in the phytoplankton community are closely linked to local oceanographic dynamics modulated by large-scale forcings, such as La Niña events and Southern Annular Mode. Wang et al. (2025), fluctuations mention a strong impact during the three La Niña years on Antarctic surface climate changes and highlight that tropical-Antarctic teleconnection links during 2023 were stronger and played a key role in these changes. NOAA (2023), The three consecutive years of La Niña conditions – a rare “triple-dip” phenomenon – had widespread impacts on the ocean and climate across the globe. Therefore, during the cold phases and greater extent of sea ice during these events may have favored water column stability and nutrient accumulation, creating conditions conducive to the predominance of diatoms typical of cold, silicate-rich environments. These phytoplankton responses highlight their role as sensitive bioindicators of regional climate change and underscore the importance of continuing long-term monitoring in the Antarctic Peninsula to understand the interactions between climate forcing, trophic structure, and marine productivity.

CONCLUSIONS

The dominance of diatom species was probably caused by decreased salinity and consumption of nitrates and phosphates, which contributed to maximum chlorophyll concentrations during the southern summers of 2023 and 2025, helping to maintain and generate surface oxygenation observed in the South Shetland Islands, Antarctica.

There was a change in the community structure of species during the study period, establishing a greater abundance of diatoms, dominated by *Rizhosolenias imbricata*, *Corethron criophylum*, *Thalassiosira rotula* during 2023, with temporary changes in the dominant species based on the importance value index compared to the southern summers of 2024 and 2025.

A correlation was determined between Thalassiosira subtilis and chlorophyll observed in the southern summer of 2023, favoured by the availability of nutrients *Coscinodiscus excentricus* and *Actinoptychus splendes* are related to chlorophyll during 2024, and there was a significant positive correlation between nitrate, nitrite, and salinity with *Coscinodiscus concinnus* and a negative correlation with phosphate in 2025.

During the study period (2023–2025), a marked dominance of diatom species was observed, probably associated with the decrease in surface salinity and the active consumption of nitrates and phosphates. These processes favored the development of high concentrations of chlorophyll-a during the austral summers of 2023 and 2025, contributing to higher primary productivity and the consequent oxygenation of the surface layers in the waters surrounding the South Shetland Islands.

A progressive change in the phytoplankton community structure was evident throughout the observation period, with greater richness and abundance of diatoms during 2023, dominated by *Rhizosolenia imbricata, Corethron criophilum*, and *Thalassiosira rotula*. In the summers of 2024 and 2025, temporal variations in the dominant species were recorded, according to the importance index values, suggesting an adaptive response of phytoplankton to the physical-chemical variability of the environment.

Likewise, a significant correlation was determined between *Thalassiosira subtilis* and the chlorophyll-a concentrations observed during the southern summer of 2023, possibly favoured by the high availability of nutrients. In 2024, *Coscinodiscus excentricus* and *Actinoptychus splendens* showed a positive association with chlorophyll, while in 2025 a significant positive correlation was identified between nitrate, nitrite and salinity with *Coscinodiscus concinnus*, and a negative correlation with phosphate, indicating a change in nutrient availability and water stratification conditions.

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