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Glacier influence on the composition and diversity of the marine phytoplankton community in Admiralty Bay, King George Island, Antarctica

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ABSTRACT. Climate change has contributed to rapid glacier retreat in the West Antarctic Peninsula, with potential implications for marine ecosystems, particularly phytoplankton communities. In this study, we examined the influence of glacier proximity on phytoplankton composition in Admiralty Bay, Antarctica, during the austral summer of 2020. In total, 12 sampling stations were established at various distances from the glacier front to collect water samples at 3 depths to quantitatively analyze phytoplankton. The community in all stations was found to be dominated by nanoflagellates (<20 µm) (95.5%), followed by diatoms (4.02%), and finally, dinoflagellates (0.47%). The diversity index (*H*') ranged from 0.07 to 1.04 bits·cell^{-1}, with the highest indices observed at stations closer to the glacier fronts and the one closest to the coast (<3 km). Based on phytoplankton community composition, 3 clusters were identified: (1) the station closest to the coast, (2) stations located between 0.66 and 1.12 km from the glacier front, and (3) stations between 2.61 and 11.10 km from the glacier front. Overall, diversity exhibited a fourth-degree polynomial relationship (R^2 = 0.35) with glacier distance. Therefore, it can be concluded that the composition of marine phytoplankton varies based on its proximity to glaciers in Admiralty Bay.

Key words: Antarctica, phytoplankton, biodiversity, community composition, glacier distance.

INTRODUCTION

The West Antarctic Peninsula is one of the regions experiencing accelerated climatic and environmental changes. Over the past 50 years, the mean annual air temperature in this region has noticeably increased 1–2 °C (Ducklow et al. 2007) and 0.56 °C per decade (Turner et al. 2014), which has greatly affected sea ice, ice shelves, and glacier systems (Steig et al. 2009, Pan et al. 2019). Consequently, the retreat of glaciers and disintegration of the ice sheet are changing hydrophysical conditions, the duration of the production period, and the structure and distribution of plankton communities in the Antarctic region (Kasyan et al. 2022).

Phytoplankton is one of the most important primary producers in Antarctica. It is the main source of food and the basis of the entire food web. Typically, on the Antarctic Peninsula, diatoms dominate phytoplankton communities; however, there are often events where other taxonomic groups dominate, such as nanoflagellates (Estrada and Delgado 1990, Lange et al. 2018). Variations in patterns could be related to physicochemical or environmental characteristics of water masses that create favorable conditions for the proliferation of different groups of organisms (Bianchi et al. 1992). One source of these changes is the influx of runoff from glaciers. Glacier water runoff and biological processes, such as zooplankton grazing, modify the abundance and dominance

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of different taxonomic groups (Knox 2007). Climate change has consequences on the physical and chemical properties of the sea; therefore, it could alter the abundance, structure, and productivity of phytoplankton communities, which in turn would affect all trophic levels of the regional food web (Moline et al. 2004, Kopczyńska 2008, Deppeler and Davidson 2017). Therefore, studying the composition of the phytoplankton community and the influence of environmental conditions is essential to understand possible ecosystem responses to global climate change, both in the short and long term.

On King George Island, the largest island of the South Shetland Islands, an unprecedented retreat of glaciers flowing into the fjords and coastal ocean has been observed (Osmanoğlu et al. 2013). Recent studies have shown the influence of glacier runoff on the composition of planktonic, benthic, and macroalgal communities in 2 Antarctic fjords in Maxwell Bay (i.e., Marian Cove and Potter Cove) mainly due to notable modifications in the physicochemical and hydrological characteristics of the water column due to glacier melt (Garcia et al. 2019, de Lima et al. 2019, Bae et al. 2021, Kim et al. 2021). In addition, Peruvian scientific campaigns to Antarctica (ANTAR) have contributed to the understanding of phytoplankton composition in Mackellar Inlet, Admiralty Bay, Bransfield Strait, King George Island, and the surroundings of Elephant Island (Sánchez and Villanueva 2001, Bonicelli et al. 2008, Ochoa et al. 2016, Baylón et al. 2019). In Admiralty Bay, research has specifically focused on phytoplankton distribution patterns and their spatiotemporal variation (Sánchez et al. 2013, Baylón et al. 2019). However, despite recent reports in other fjords of King George Island, studies on the relationship between phytoplankton and the influence of glaciers in Admiralty Bay are scarce. Therefore, the present research aimed to evaluate the influence of glacier retreat on the composition and diversity of marine phytoplankton, considering the distance (proximity or distance) from the glacier front, in Admiralty Bay, King George Island, Antarctica.

Materials and methods

Study area

The study was carried out in Admiralty Bay, King George Island, Antarctica. This large fjord of tectonic origin, with a surface area of 122 km^2 and a maximum depth of 535 m, has 3 main inlets (Ezcurra, Mackellar, and Martel) and a wide opening to the Bransfield Strait (8.25 km wide). Approximately half of the coast (83.40 km) is composed of glaciers and polar ice caps (Siciński et al. 2011). In addition, Admiralty Bay has a complex hydrology determined by water exchange with Bransfield Strait, freshwater runoff, and local processes (Szafranski and Lipski 1982).

Sampling stations were established along Admiralty Bay (Fig. 1) based on the proximity to glacier fronts. In total, 12 sampling stations were established, including stations close to glaciers (direct contribution of glacier runoff) located inside Mackellar Inlet (M01, M02, M03, M04, M05, and M06), stations far from glacier fronts (without direct contribution from glacier runoff) located towards the Bransfield Strait (M07, M08, and M09), and other stations on the outskirts of the bay (M10, M11, and M12). In addition, aerial photographs of the sampling stations were taken.

Sampling

Sampling was carried out through the Peruvian scientific campaign ANTAR XXVII between January 14 and 19, 2020, during the austral summer. At the stations located in Mackellar Inlet (M01 to M06), samples were collected aboard a Zodiac-type vessel, using a 5-L Niskin bottle. At the other stations (M07 to M12), samples were collected with an oceanographic rosette with a conductivity temperature depth (CTD) profiler aboard the Peruvian Navy ship *Carrasco* (polar oceanographic research vessel [BOP]-171) of the Peruvian Navy. Water samples were taken from the photic layer of the water column at depths of 0, 10, and 20 m (Cermeño et al. 2014). Samples were collected in 250-mL flasks and fixed with formaldehyde to obtain a final concentration of 0.4% for subsequent quantitative analysis of phytoplankton. In addition, at each station, a surface trawl was carried out with a phytoplankton net (75-µm mesh opening) for 10 min; these samples were fixed with formaldehyde to obtain a final concentration of 2% for subsequent qualitative analysis of phytoplankton. Due to logistic limitations, we were unable to acquire a phytoplankton net with a smaller mesh size (20 µm); therefore, the net we worked with had a 75-µm mesh size, which provided valuable information on the largest members of the phytoplankton community.

Measurement of physicochemical parameters

The physicochemical parameters of the water column were determined in situ when water samples were collected. Water column temperature, salinity, and dissolved oxygen data were recorded using a portable Multi 3630 IDS meter (WTW, Xylem Analytics, Washington, D.C., USA) for stations within Mackellar Inlet. For the other stations, we used an SBE 19 PLUS CTD profiler (Sea-Bird Scientific, Bellevue, USA). Records were also taken in Bransfield Strait with the CTD profiler. In addition, we downloaded and processed physicochemical data of Admiralty Bay collected during January 2020 at the 3 depths available in the PANGEA repository (https://doi.org/10.1594/PANGAEA.947909), which were obtained by Osińska et al. (2023).

Phytoplankton analysis

For qualitative analysis, we applied specific techniques to observe microscopic structures. For diatoms, we cleaned

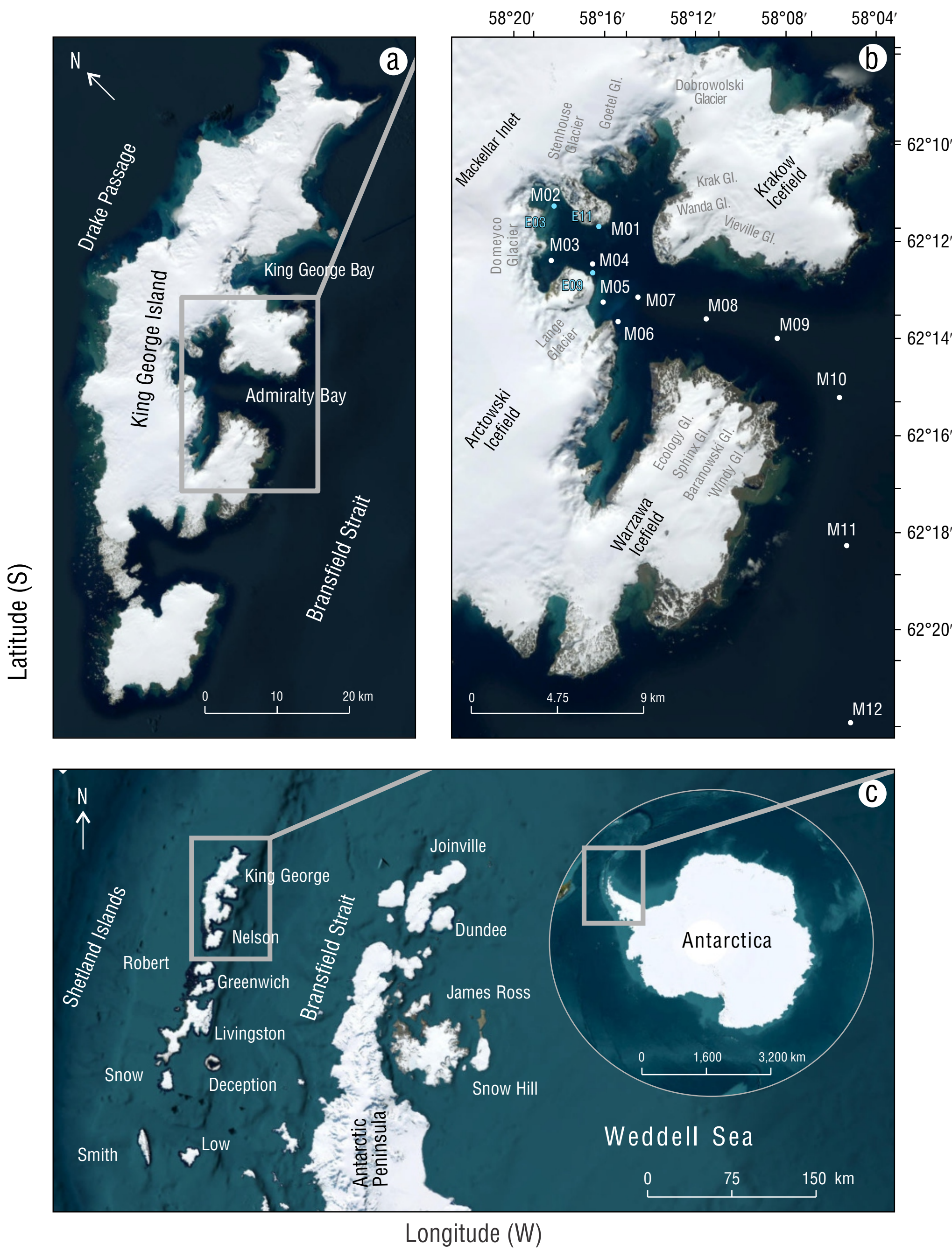

Figure 1. Map of sampling stations in Admiralty Bay, King George Island, Antarctica. (**a**) King George Island, (**b**) Admiralty Bay, (**c**) Antarctica.

and stained the valves (Battarbee 1986); for dinoflagellates, we stained the organisms with Lugol or methylene blue. This analysis allowed us to determine frequencies of phytoplankton >75 µm and microalgae <75 µm that were trapped in the net during trawling.

Quantitative analyses were carried out according to the Utermöhl sedimentation technique (Lund et al. 1958), and the results of abundance were expressed in number of cells per liter (cell·L^{-1}). Each sample was gently homogenized and then a subsample was placed in 50-mL sedimentation cylinders for a time of no less than 48 h. To identify and count abundant organisms with sizes <20 µm, we used an inverted microscope (DM IL LED, Leica, Wetzlar, Germany) (400× magnification, 25-mm^2 area). Organisms >20 µm and with low abundances were counted in the whole chamber (200× magnification). In each sample, at least 100 cells were counted along randomly chosen chamber transects.

Phytoplankton taxa were identified according to the keys edited by Frenguelli (1943), Balech (1944), Frenguelli and Orlando (1958), Balech (1976), Sournia et al. (1979), Priddle and Fryxell (1985), Medlin and Priddle (1990), Round et al. (1990), Hasle and Syvertsen (1997), and Steidinger and Tangen (1997). Diatoms and dinoflagellates were identified to the genus or species level. However, some organisms could not be identified, such as the group of small flagellates, which were grouped and classified as nanoflagellates (<20 µm).

Distance to the glacier front

The average distance from a sampling station to glacier fronts with direct meltwater input was established using the Sentinel-2 satellite image of January 19, 2020. ArcGIS v10.7 software was used to display and process the satellite image. Band variations were done with the RGB 482 combination to visualize sediment fluxes. We identified the contributions of the closest glacier fronts by visualizing the information in *shapefile* format, which delimits the contours of glaciers in the Antarctic region in polygon form. We used this information to plot and measure the distance to each station.

Statistical analyses

The composition and statistical analyses were performed with the data from the quantitative phytoplankton analysis of water samples taken with Niskin bottles. Statistical analyses were performed in R v.3.6.3 using the 'vegan' package (Oksanen et al. 2018). We calculated relative abundance, Chao-1 index (Chao), Shannon–Wiener index (H'), and Pielou evenness index (J) for each depth and station. For multivariate analyses, phytoplankton abundance data (cell·L^{-1}) were transformed (log [x + 1]). Tests for normality of the transformed abundance data were performed using the Shapiro–Wilk test. The similarity of phytoplankton associations between stations was analyzed with the Bray–Curtis index. The generated dissimilarity index matrix was subjected to hierarchical classification analysis (CLUSTER) or cluster analysis and expressed in a dendrogram using the unweighted pair group method with arithmetic mean (UPGMA). Statistical differences between the groups formed with the cluster analysis were tested using a permutational multivariate analysis of variance (PERMANOVA), a non-parametric test. In addition, with data of the main species, a principal component analysis was done with Python in Google Colaboratory to find statistical differences between 2 components: the stations closest and farthest from the glacier. With the information obtained from the cluster analysis, groups (clusters) were defined to analyze similarity percentages with a SIMPER analysis and identify the taxa responsible for the differences between the groups. We evaluated the relationship between the average species diversity (H') and the distance to the glacier front with a polynomial regression test, which allowed us to determine the best fit for the data.

Results

Hydrological conditions and their association with the distance to glacier fronts

The representative physicochemical parameters of each station in the bay were compiled and detailed in Table 1. The surface temperature of stations M01–M07 ranged between 1.50 and 2.20 °C, and it was slightly higher at stations M10 to M12, with values between 1.98 and 2.23 °C. Salinity also increased from nearby stations M01–M06 (32.80–33.10‰) to distant stations M07–M12 (33.40–33.80‰). Conversely, dissolved oxygen was higher for nearby stations (M01–M06) and decreased for distant ones (M07–M12), with values between 11.22 and 11.39 mg·L^{-1} and 7.68 and 11.25 mg·L^{-1}, respectively (Fig. 2). Temperature, salinity, and dissolved oxygen in the water column behaved similarly at 10 and 20 m, with slight variations at the surface.

Frequency of phytoplankton species

The diatoms *Porosira glacialis* (100%), C*orethron criophilum* (83.33%), *Licmophora antarctica* (83.33%), *Haslea trompii* (66.67%), *Fragilariopsis cylindrus* (50%), and *Thalassiosira antarctica* (50%) predominated in the net samples. Among the dinoflagellates, *Pronoctiluca pelagica* (66.67%) and *Gyrodinium* sp. (50%) were the most frequent species (Fig. 3).

Phytoplankton composition and abundance

We identified 33 species: 24 diatoms, 6 dinoflagellates, and 3 nanoflagellates. Total phytoplankton abundance varied between 6.09×10^4 cell·L^{-1} and 10.15×10^5 cell·L^{-1} and was dominated by nanoflagellates (<20 µm) (95.5%), followed by diatoms (4.02%) and, finally, dinoflagellates (0.47%). At 0, 10, and 20 m depth, the community was mostly composed of nanoflagellates (96.37%, 94.68%, and 95.41%, respectively), followed by diatoms (3.21%, 4.88%, and 4.00%, respectively) and, finally, dinoflagellates (0.42%, 0.45%, and 0.59%, respectively). The highest abundance values were recorded at stations M08 and M09; in regards to depth, abundance was higher at the surface compared to 20 m depth (Fig. 4). The abundance of diatoms was higher at stations closest to the coast and the glacier front (M01–M06) and decreased towards the farthest stations (M07–M12); conversely, the abundance of dinoflagellates and nanoflagellates increased at stations M07–M09 and slightly decreased at stations M10–M12. The relative abundance (%) for the totality of the samples (Fig. 5) places unidentified nanoflagellates in first place, followed by *Leucocryptos marina* and *Pseudo-nitzschia delicatissima* group (15.83% and 3.49%, respectively).

Richness and diversity

In general, the values of Shannon–Wiener diversity index (*H*′), which varied between 0.07 (M05 at 0 m) and 1.04 bits·cell^{-1} (M01 at 10 m), indicated low diversity due to the dominance of few species. Diversity in the water column was higher at 10 m depth and lower at the surface for all stations, except at station M12, where diversity was higher at the surface (Table 2). Species richness was highest at station M06 at 20 m and at station M01 at 0 m, with Chao-1 index values of 18 and 17, respectively. At 10 m, station M01 showed greater equity in the distribution of the abundance of species. Evidently, stations close to the glaciers (M01, M02, M03, and M6) had higher *H*′ diversity indices compared to the farthest station M12 (Fig. 6a), with the exception of M04 and M05, which had low indices that were similar to those of M12. This pattern was more evident at depths of 10 m (Fig. 6c) and 20 m (Fig. 6d) compared to the surface (Fig. 6b).

Throughout Admiralty Bay, we identified common species from Antarctic waters such as *T. antarctica*, *P. delicatissima* group, *C. criophilum*, *P. glacialis*, *H. trompii*, *Fragilariopsis kerguelensis*, *Gyrodinium lachrymal*, and *Gymnodinium* sp. (Table 3). Throughout the water column, the abundance of diatoms of the class Bacillariophyceae was highest at stations close to the glaciers (M01–M06) and decreased between stations M07 and M12. In contrast, dinoflagellates of classes Dinophyceae and Noctilucophyceae (Fig. 7) increased in abundance between stations M07 and M12; this was observed for the species *Gyrodinium* sp. (Fig. 5) and *P. pelagica*.

Similarity in phytoplankton community composition

To analyze the relationship between the stations, we applied clustering techniques with integrated abundance data of the 3 depths, which were subsequently represented by a dendrogram. Based on the composition and abundance of species, we distinguished 3 main clusters. Figure 8 shows that cluster "A" grouped only the station closest to the coast (M01). Cluster "B" grouped 6 distant stations (M07 to M12). Cluster "C" grouped 5 stations close to the glaciers (M02 to M06). The PERMANOVA analysis between these clusters showed that there were significant differences ($P < 0.05$) between the 3 clusters, with the highest found between "B" and "A" ($P = 0.001$) and "B" and "C" ($P = 0.001$) and less between "A" and "C" ($P = 0.018$).

The principal component analysis graph was made with the main species and sampling stations (Fig. 9). The explained variance of the 2 principal components is shown: the first principal component explains 29.51% of the total variation of the original data and the second component explains 22.91%. Together, the 2 main components explain around 52.42% of the total variation (an acceptable percentage). Furthermore, the analysis revealed 3 clear groups equal to those obtained by the cluster analysis; however, an

Table 1. Coordinates and physicochemical conditions of sampling stations and distance to the glacial fronts in Admiralty Bay, King George Island, Antarctica.

Station	Latitude South	Longitude West	Sampling date	Dissolved oxygen (mg·L^{-1})	Temperature (°C)	Salinity (‰)	Average distance to the glacier front (km)
M01	58°24′54″	62°5′24″	19/01/2020	11.39	1.60	33.00	2.92
M02	58°26′24″	62°4′4.8″	19/01/2020	11.22	2.20	32.80	0.66
M03	58°28′30″	62°5′2.4″	18/01/2020	11.33	1.80	33.30	1.12
M04	58°26′56.4″	62°6′0″	18/01/2020	11.26	1.50	33.10	0.81
M05	58°28′8.4″	62°7′1.2″	17/01/2020	11.25	1.65	33.00	0.96
M06	58°28′22.8″	62°7′44.4″	17/01/2020	11.24	1.72	33.10	0.43
M07	58°26.370′	62°7.662′	16/01/2020	11.25	1.64	33.10	2.61
M08	58°24.357′	62°9.585′	16/01/2020	11.06	1.76	33.20	3.83
M09	58°22.118′	62°11.524′	15/01/2020	10.79	1.87	33.30	4.14
M10	58°22.088′	62°14.087′	15/01/2020	10.22	1.98	33.50	5.18
M11	58°28.617′	62°17.300′	14/01/2020	8.77	1.97	33.70	6.24
M12	58°36.683′	62°21.026′	14/01/2020	7.60	2.23	34.00	11.1

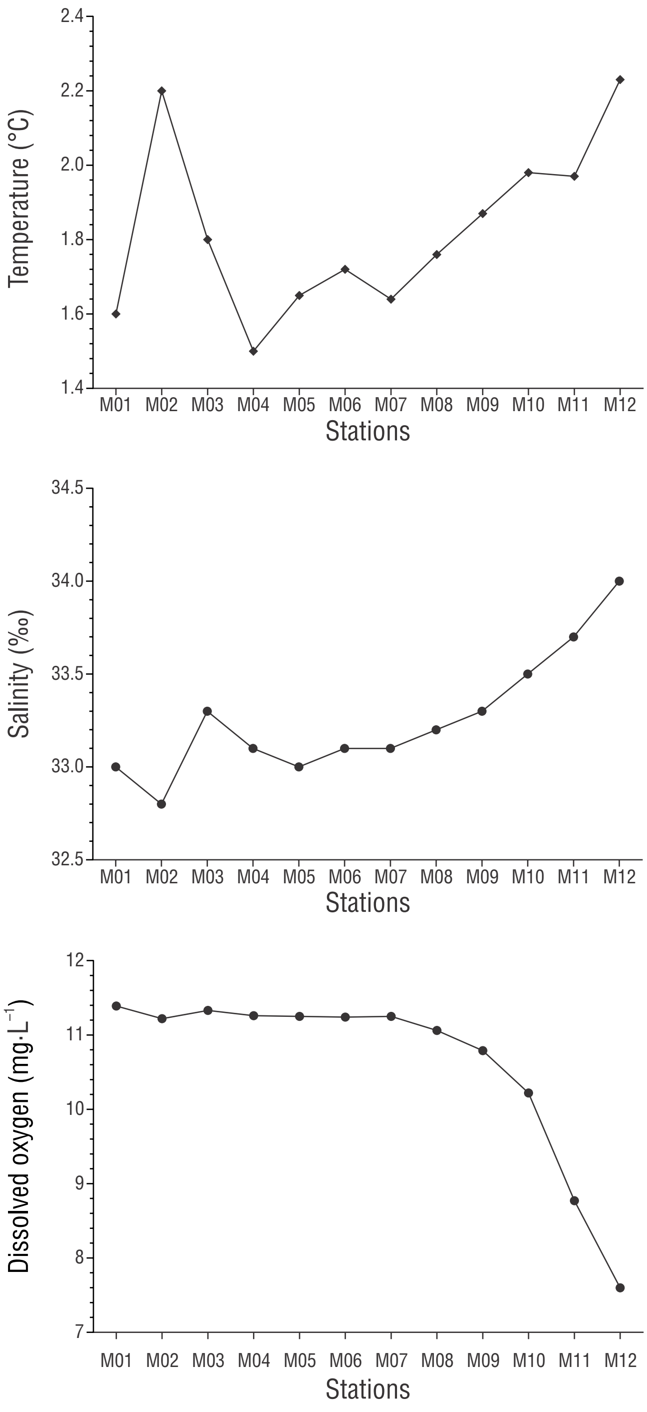

Figure 2. Temperature, salinity, and surface dissolved oxygen (0 m) of sampling stations in Admiralty Bay during the austral summer of 2020.

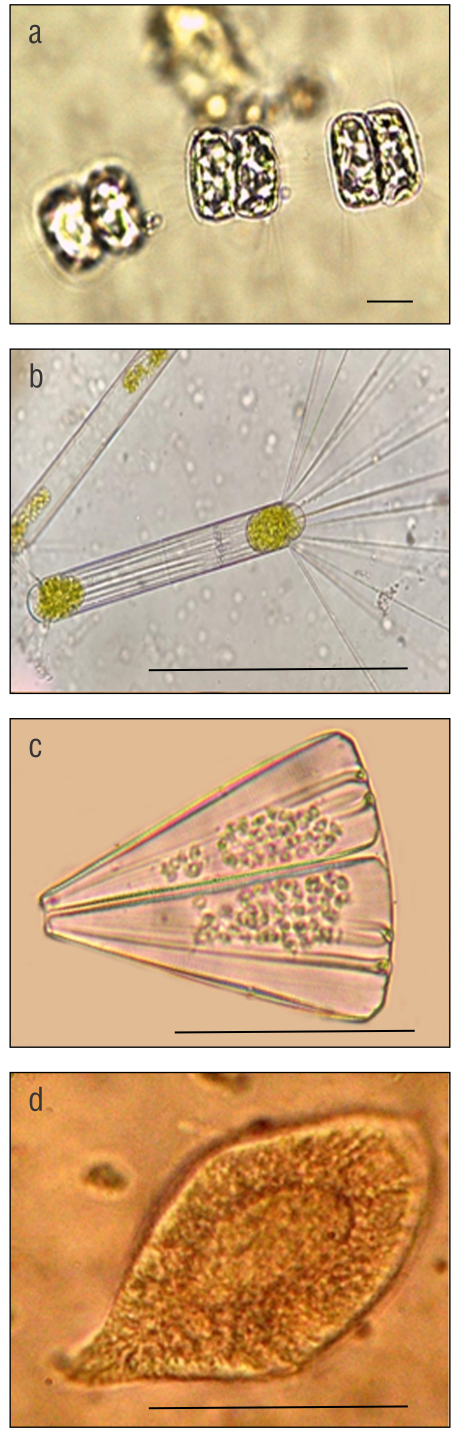

Figure 3. Most frequent phytoplankton species reported in the ANTAR XXVII campaign in the austral summer of 2020. (**a**) *Porosira glacialis*, (**b**) *Corethron criophilum*, (**c**) *Licmophora antarctica*, (**d**) *Gyrodinium* sp. (**a**) The scale bar of the optical microscope is 10 µm, (**b**–**d**) the scale bar of the optical microscope is 50 µm.

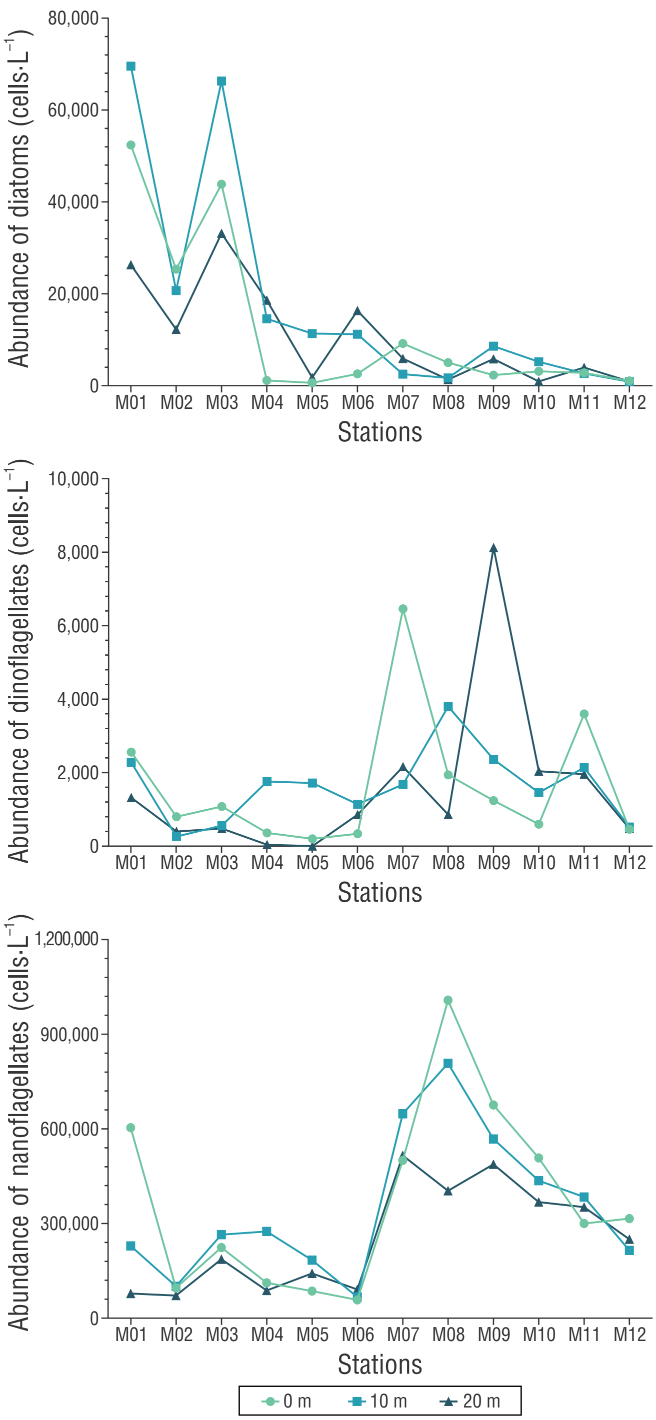

Figure 4. Abundance of phytoplankton groups at the 12 sampling stations and in the water column during the austral summer of 2020 in Admiralty Bay, King George Island.

additional group made up of a distant station was observed. The first group consisted of the nearest stations M02, M03, M04, M05, and M06; the second, of the 5 distant stations (M07, M08, M09, M10, and M11); the third, of station M01; and the fourth, of station M12.

Species contribution to average dissimilarity between groups

Table 4 shows the results of the SIMPER analysis that was done to evaluate the phytoplankton species that contributed significantly to the dissimilarity between the clusters (A, B, and C). Evidently, 9 species contributed more than 50% of the dissimilarity between the analyzed clusters, of which *L. marina* and different species of diatoms contributed more. The dissimilarity between cluster A and B was influenced by the greater contribution of the nanoflagellate *L. marina* (3.29%), followed by the diatoms *C. cryophilum* (2.52%) and *F. cylindrus* (2.41%). For A and C, the diatoms *T. antarctica* (2.91%), *H. trompii* (2.62%), and *F. cylindrus* (2.59%) were the most influential. Between B and C, the species that contributed the most to the dissimilarity were *L. marina* (5.26%), *T. antarctica* (2.38%), and the dinoflagellate *Gyrodinium* sp. (2.35%).

Association between the diversity index and the distance to glacier fronts

To establish the relationship between species diversity (each station average) and the average distance to the glacier front (Table 1), linear and polynomial regressions were done. The fourth-degree polynomial model had the best fit for the data (Fig. 10a) with a coefficient of determination (R^2) of 35.40%. This result shows that diversity increased progressively from the coast and reached maximum values at 3–4 km from the glacier front and had lower values at the most distant stations.

Station M01 was closer to the coast but farther from the nearby glacier than other stations close to the glacier front, such as station M02, which received direct input from the surrounding glaciers. On the other hand, compared to other stations in the area, stations M04 and M05 (close to the glaciers) showed a marked decrease in diversity. Unlike for other nearby stations, aerial photographs (Fig. 10b) for M04 and M05 showed large sediment plumes at the surface layer that probably affected the abundance at these stations. Therefore, diversity varied at stations close to glaciers (M01–M06) as their distance from the glacier decreased; nonetheless, distant stations showed a more stable pattern of diversity that decreased as the distance to the glacier increased.

Discussion

In recent years, considerable changes have been detected in the structure and biomass of the Southern Ocean phytoplankton community (Deppeler and Davidson 2017). In particular, a notable frequency of nanoflagellate blooms has been evidenced, especially in Antarctic coastal areas (Kopczyńska 2008, Pan et al. 2020, Jeon et al. 2023). Antarctica is enduring one of the highest rates of climate change, with reports of extreme temperature events (heat/cold) (Hobday et al.

2016). These events are the main drivers of marine heatwaves (MHW) that affect the structure of marine communities at all trophic levels (Hobday et al. 2016, Smale et al. 2019). In Potter Cove, also located on King George Island, MHWs occurred for several days in the austral summer of 2020. These conditions altered the biomass of most plankton species, promoting the dominance of unidentified nanoflagellates (Latorre et al. 2023). This study showed that nanoflagellates were numerically the most abundant group in Admiralty Bay during the austral summer of 2020; this further evidenced the trend for the summer season, which could be related to the effects of MHWs.

Furthermore, Baylón et al. (2019) and Ochoa et al. (2016) reported similar results for Mackellar Inlet during the austral summer of 2012 and Bransfield Strait during the austral summer of 2006, respectively. Likewise, some reports show the year-round dominance of nanoflagellates over diatoms in Admiralty Bay. The dominance of nanoflagellates can be attributed to the stability that results from the almost homogeneous distribution of temperature and salinity in the water column (Kopczyńska 2008, Baylón et al. 2019). Biggs et al. (2019) attribute the reduction in total phytoplankton biomass and the shift from large phytoplankton (diatoms) to smaller flagellate species to changes associated with low salinities, high temperatures, and strong vertical stratification. In the austral summer of 2020, physicochemical values were almost uniform in the water column (up to 20 m depth), which prompted the proliferation and dominance of nanoflagellates. Among the most dominant diatom species, we identified *P. delicatissima* group, *P. glacialis*, and *T. antarctica*. This result coincides with reports from the austral summer of 2006 (Ochoa et al. 2016) and the austral summers of 2012 and 2013 (Baylón et al. 2019).

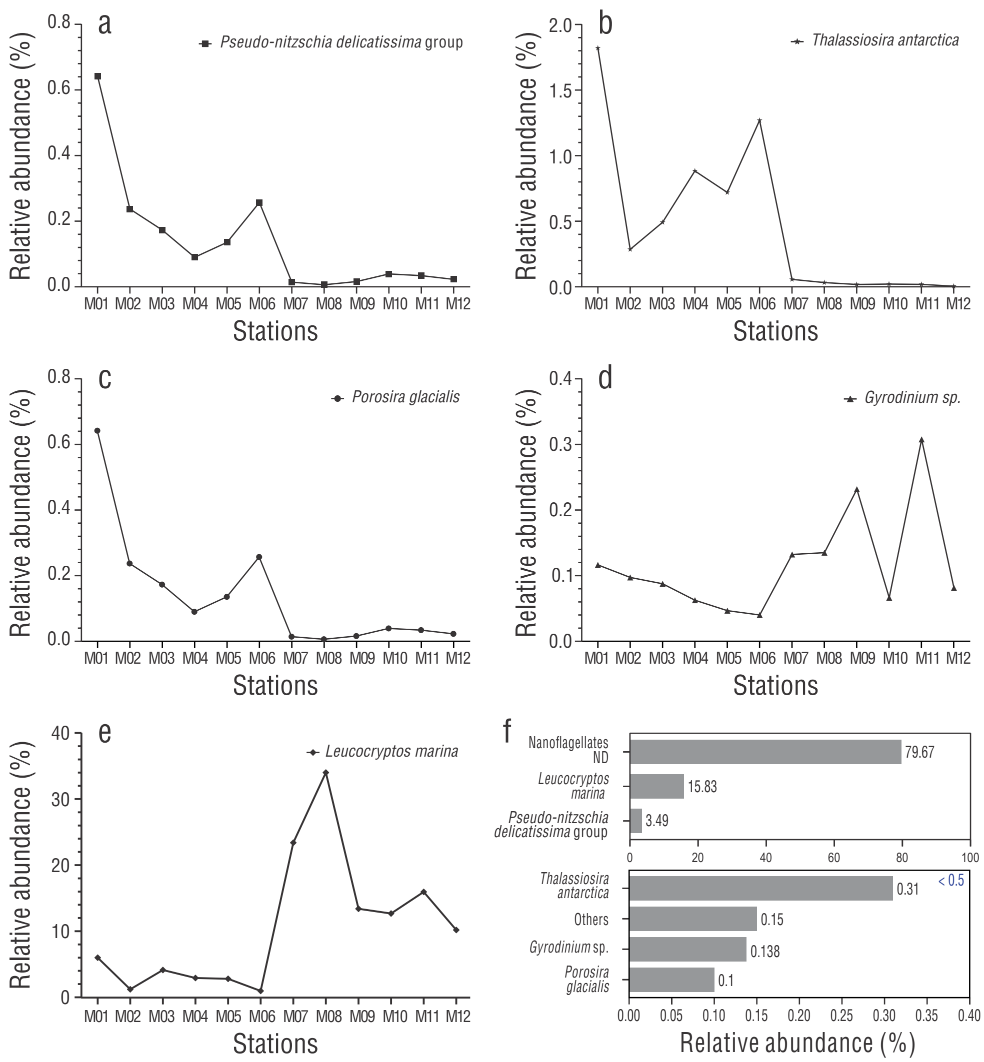

Figure 5. Relative abundance (%) of phytoplankton species from the average of 3 depths (0, 10, and 20 m) during the austral summer of 2020 in Admiralty Bay, King George Island. (**a**) *Pseudo-nitzschia delicatissima* group, (**b**) *Thalassiosira antarctica*, (**c**) *Porosira glacialis*, (**d**) *Gyrodinium* sp., (**e**) *Leucocryptos marina*, (**f**) total relative abundance of phytoplankton species. ND: unidentified.

Table 2. Abundance (AB), Chao-1 indices (Chao), Shannon–Wiener diversity (*H*′) and Pielou evenness (*J*), recorded for the ANTAR XXVII campaign (austral summer 2020).

	Depth											
	0 m				10 m				20 m			
Stations	AB	Chao	*H*′	*J*	AB	Chao	*H*′	*J*	AB	Chao	*H*′	*J*
M01	658,960	17	0.58	0.2	300,840	16	1.04	0.38	105,640	14	0.87	0.33
M02	122,160	10	0.6	0.26	121,980	11	0.51	0.21	84,660	12	0.67	0.27
M03	268,960	10	0.52	0.23	331,880	11	0.77	0.32	220,660	12	0.68	0.27
M04	113,520	7	0.09	0.05	291,320	11	0.48	0.2	106,640	7	0.52	0.27
M05	86,820	8	0.07	0.03	197,280	15	0.5	0.18	143,800	10	0.21	0.09
M06	60,920	14	0.25	0.09	79,740	12	0.61	0.25	108,200	18	0.63	0.22
M07	515,660	10	0.54	0.23	652,200	12	0.64	0.26	524,080	9	0.69	0.32
M08	1,014,980	9	0.66	0.3	813,500	9	0.71	0.32	406,200	9	0.68	0.31
M09	679,560	13	0.41	0.16	578,960	12	0.6	0.24	501,940	13	0.44	0.17
M10	511,720	12	0.41	0.17	442,660	12	0.57	0.23	370,960	10	0.32	0.14
M11	306,400	11	0.56	0.23	388,820	9	0.61	0.28	357,920	11	0.4	0.17
M12	317,520	8	0.5	0.24	216,400	10	0.36	0.16	251,420	7	0.15	0.08

Compared to what was reported for the austral summers of 2012 and 2013 (Baylón et al. 2019), the values of the diversity indices for Mackellar Inlet (M01, M02, M03, and M04) were lower than those previously reported for relatively close stations (E03, E09, and E11) (Fig. 1). This is mainly due to the abundance of nanoflagellates (<20 µm), compared to those of other years. In addition, sea salinity varied between 34‰ and 34.51‰ during the summer of 2012 and between 33.69‰ and 34.04‰ during the summer of 2013; these values are higher than those of the summer of 2020 (32.80–33.10‰). This suggests that salinity has been decreasing for almost a decade in specific areas of Mackellar Inlet. The change in salinity could be associated with the increase of freshwater that resulted from glacier retreat, which was probably favored by the temperature increase and MHW reported for the summer of 2020 (Latorre et al. 2023). Meltwater runoff can produce changes in sea temperature and dissolved organic matter content and increase pH, turbidity, and dissolved oxygen values; this has been reported for other fjords in Admiralty Bay (Osińska et al. 2021). These changes could have encouraged nanoflagellate species to take advantage of this new habitat and become more common during the summer, which could intensify as glacier runoff increases.

Of the 3 clusters formed, one grouped distant stations (>3 km), indicating that they have similar phytoplankton compositions, which was corroborated with the previous PERMANOVA analysis ($P < 0.05$). On the other hand, we evidenced that station M01, the closest to the coast, had a small difference in phytoplankton composition when compared to other stations close to the glacier (<3 km). This difference could be caused by the input of water with terrigenous material, since M01 is not in direct contact with the glacier. These differences in phytoplankton composition between nearshore and offshore stations have been observed around the Antarctic Peninsula, where nearshore communities are mostly dominated by benthic or pelagic diatoms and have high concentrations of Chl*a*, and open ocean areas are dominated by nanoflagellates, which replace diatoms in communities (Mendes et al. 2012, Lange et al. 2018). In recent years, the predominance of phytoplankton taxonomic groups in coastal areas has shifted from diatoms to phytoflagellates (Lange et al. 2014, 2018), which suggests marked changes in the water column.

Abundance and species richness were very low at stations M04 and M05. Large plumes of turbid sediment from glaciers, evidenced in aerial photographs, probably caused these results (Fig. 10b). Progressive subglacial and surface erosion during melting seasons generates extensive sediment columns, mainly in coastal and glacier areas (Monien et al. 2017). Eroded sediments transported on the surface create shading that affects primary producers (Pan et al. 2020). In general, nanoflagellates have been documented to dominate numerically in areas with attenuated light conditions (Kopczynska 1992); conversely, under these light conditions, diatoms show limited growth (El-Sayed 1978). Stations with lower diversities, where this limitation was evidenced by lower values of diatom abundance at the surface, reflected this. However, some diatoms may have adapted and be competitive under such conditions (Biggs et al. 2022); therefore, to better understand what causes low diversity in the aforementioned stations, it would be necessary to expand the study to different periods.

In particular, cluster A, which includes the station closest to the coast, showed an important contribution of *F. cylindrus*, which is consistent with its association with

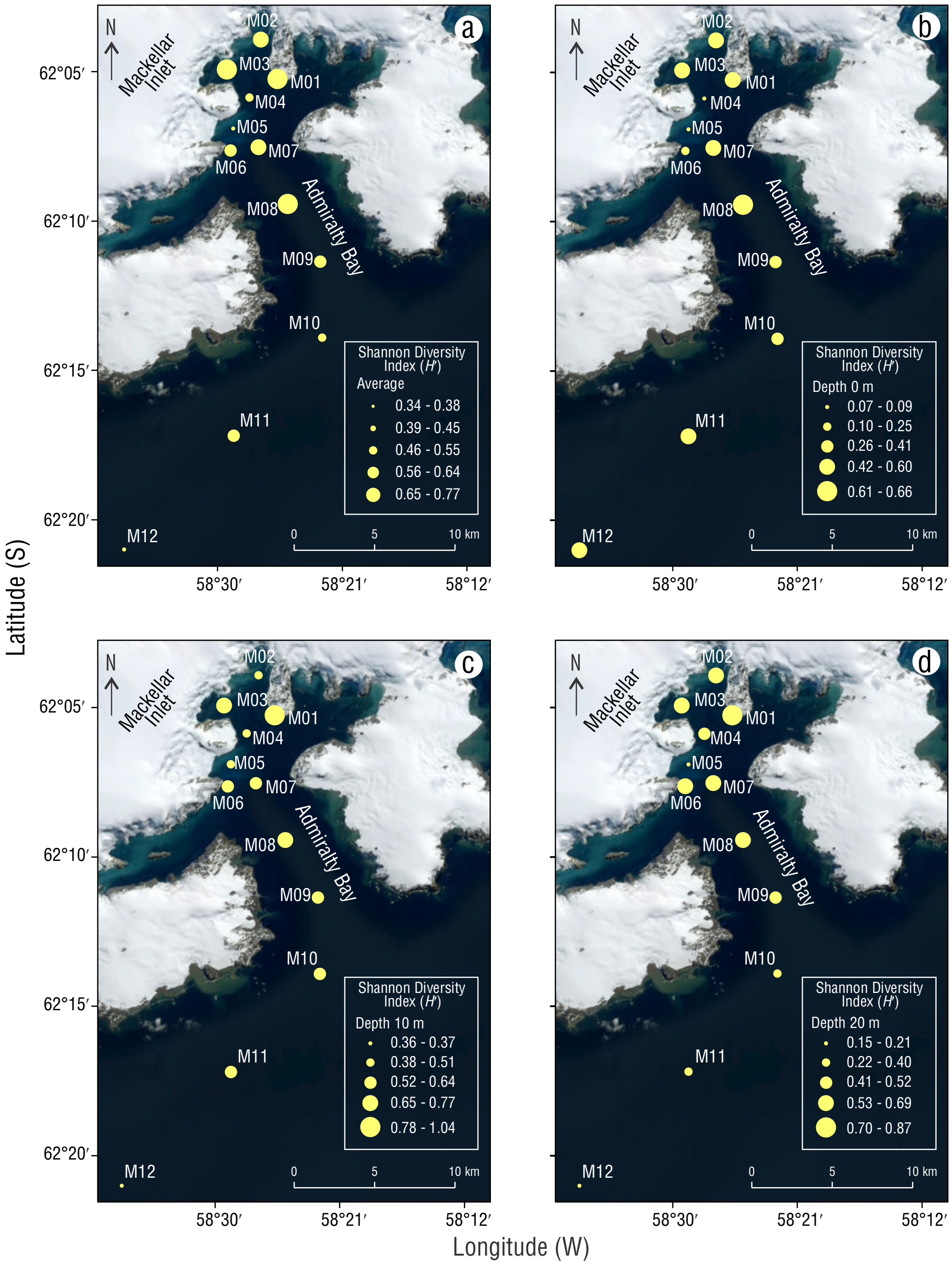

Figure 6. Shannon–Wiener diversity indices (*H*′) in the water column (0 m, 10 m, and 20 m) recorded for the ANTAR XXVII campaign (austral summer 2020). (**a**) Diversity index of the integrated data from each station, (**b**) diversity index at surface level (depth 0 m), (**c**) diversity index at a depth of 10 m, (**d**) diversity index at a depth of 20 m.

Table 3. List of diatom, dinoflagellate, and nanoflagellate species at 3 depths in Admiralty Bay, during the austral summer of 2020.

Code	Species	Group	Depth		
			0 m	10 m	20 m
Sp1	*Achnanthes brevipes*	Pennate diatoms	X		
Sp2	*Chaetoceros concavicornis*	Centric diatoms			X
Sp3	*Cocconeis pinnata*	Centric diatoms	X	X	X
Sp4	*Cocconeis* sp.	Pennate diatoms	X	X	X
Sp5	*Corethron criophilum*	Centric diatoms	X	X	X
Sp6	*Coscinodiscus* sp.	Centric diatoms	X		X
Sp7	*Eucampia antarctica*	Centric diatoms		X	X
Sp8	*Fragilariopsis cylindrus*	Pennate diatoms	X	X	X
Sp9	*Fragilariopsis kerguelensis*	Pennate diatoms	X	X	X
Sp10	*Gyrosigma fasciola*	Pennate diatoms			X
Sp11	*Haslea trompii*	Pennate diatoms	X	X	X
Sp12	*Licmophora antarctica*	Pennate diatoms	X	X	X
Sp13	*Licmophora* sp.	Pennate diatoms	X	X	X
Sp14	*Navicula* sp.	Pennate diatoms	X	X	X
Sp15	*Navicula directa*	Pennate diatoms	X	X	X
Sp16	*Nitzschia* sp.	Pennate diatoms			X
Sp17	*Pleurosigma* sp.	Pennate diatoms		X	
Sp18	*Porosira glacialis*	Centric diatoms	X	X	X
Sp19	*Pseudo-nitzschia delicatissima* group	Pennate diatoms	X	X	X
Sp20	*Rhizosolenia truncata*	Centric diatoms		X	
Sp21	*Thalassiosira antarctica*	Centric diatoms	X	X	X
Sp22	*Thalassiosira* sp.	Centric diatoms		X	
Sp23	*Tripterion margaritae*	Pennate diatoms	X	X	X
Sp24	*Tropidoneis antarctica*	Centric diatoms			X
Sp25	*Amphidinium* sp.	Unarmored dinoflagellates		X	
Sp26	*Gymnodinium* sp.	Unarmored dinoflagellates	X	X	X
Sp27	*Gyrodinium* sp.	Unarmored dinoflagellates	X	X	X
Sp28	*Gyrodinium lachryma*	Unarmored dinoflagellates	X	X	X
Sp29	*Pronoctiluca pelagica*	Unarmored dinoflagellates	X	X	X
Sp39	*Protoperidinium defectum*	Armored dinoflagellates		X	X
Sp31	*Leucocryptos marina*	Other	X	X	X
Sp32	*Tetraselmis* sp.	Other		X	
Sp33	Nanoflagelados ND	Other (phytoflagellates)	X	X	X

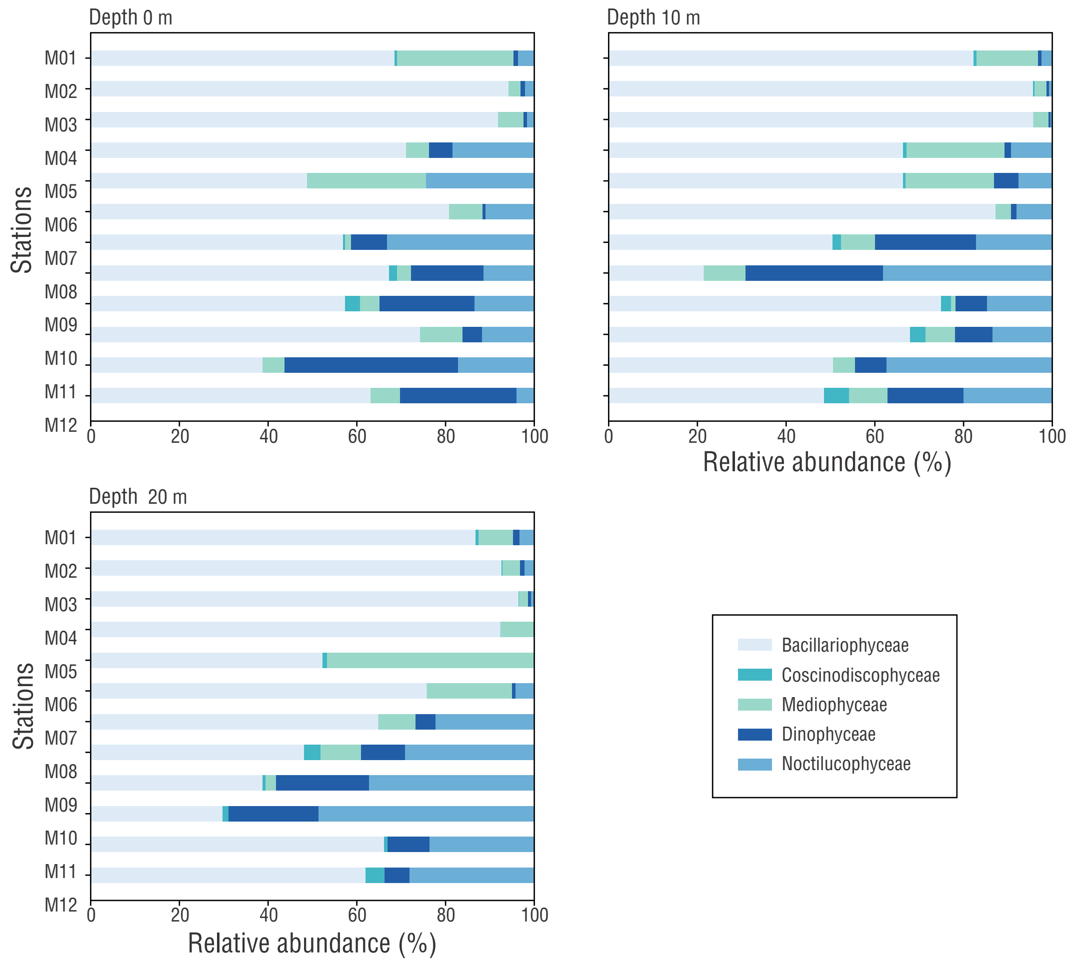

Figure 7. Relative abundance of diatom and dinoflagellate classes at 3 depths during the ANTAR XXVII scientific campaign (austral summer 2020) in Admiralty Bay, King George Island.

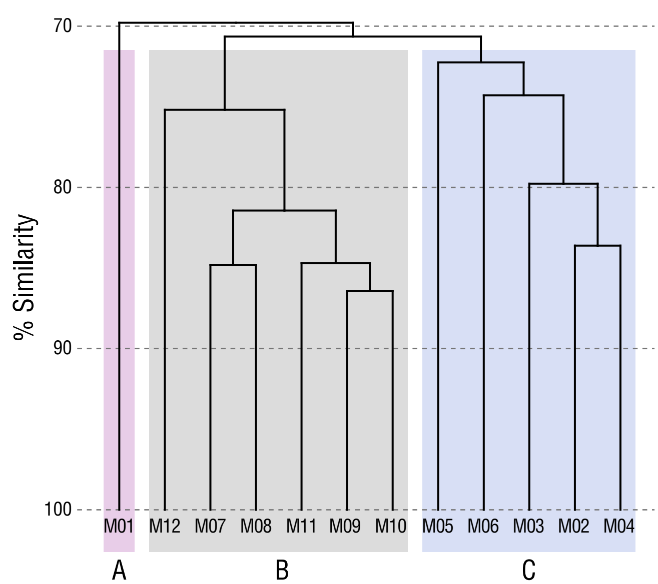

Figure 8. Analysis of the phytoplankton community at the sampling stations. Dendrogram of similarity of the phytoplankton community at all sampling stations.

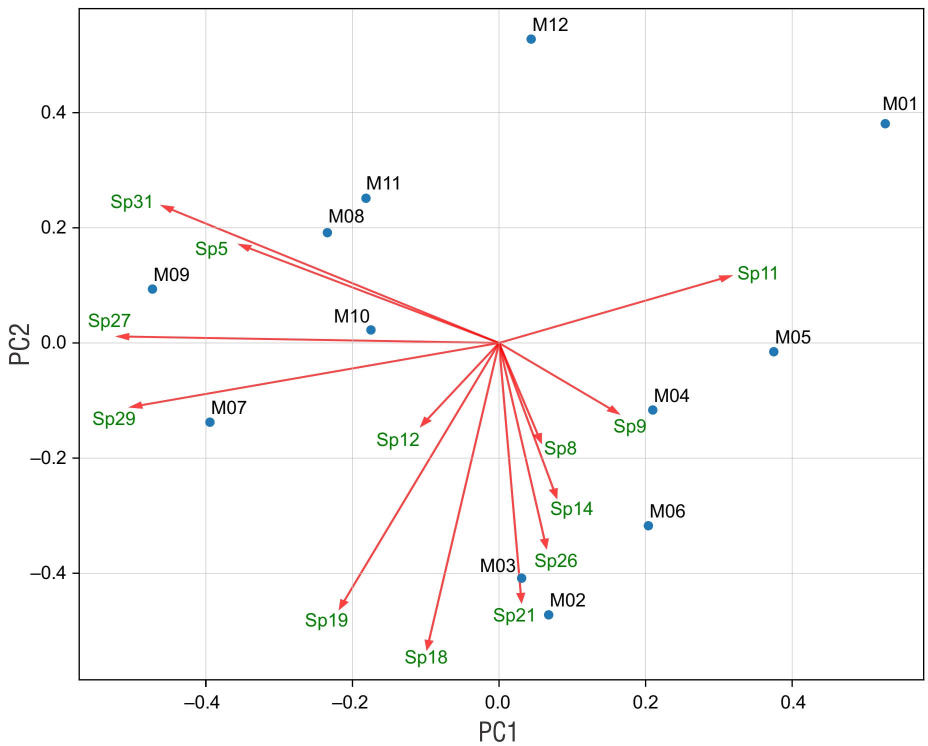

Figure 9. Principal component analysis of the main phytoplankton species at 12 sampling stations during the austral summer of 2020 in Admiralty Bay, King George Island.

Table 4. Result of the SIMPER analysis for the contribution of species to the dissimilarity between the generated clusters (A, B, and C).

	A-B		A-C		B-C	
Species	%AVG	%CUM	%AVG	%CUM	%AVG	%CUM
Leucocryptos marina	3.29	9.24	-	-	5.26	14.65
Corethron criophilum	2.52	16.3	1.61	51.62	1.91	33.14
Fragilariopsis cylindrus	2.41	23.07	2.59	25.14	-	-
Haslea trompii	2.32	29.57	2.62	17.14	1.49	46.34
Thalassiosira antarctica	1.84	34.72	2.91	9.02	2.38	21.28
Licmophora antarctica	1.67	39.41	1.62	46.63	1.68	37.83
Gymnodinium sp.	1.65	44.04	1.74	36.51	-	-
Gyrodinium sp.	1.61	48.55	-	-	2.35	27.82
Navicula sp.	1.53	52.84	-	-	-	-
Porosira glacialis	-	-	1.93	31.12	1.47	50.44
Pseudo-nitzschia delicatissima group	-	-	1.65	41.62	1.44	54.45
Fragilariopsis kerguelensis	-	-	1.6	56.57	-	-
Pronoctiluca pelagica	-	-	-	-	1.57	42.2

%AVG = Average contribution percentage; %CUM = Percentage of accumulated contribution.

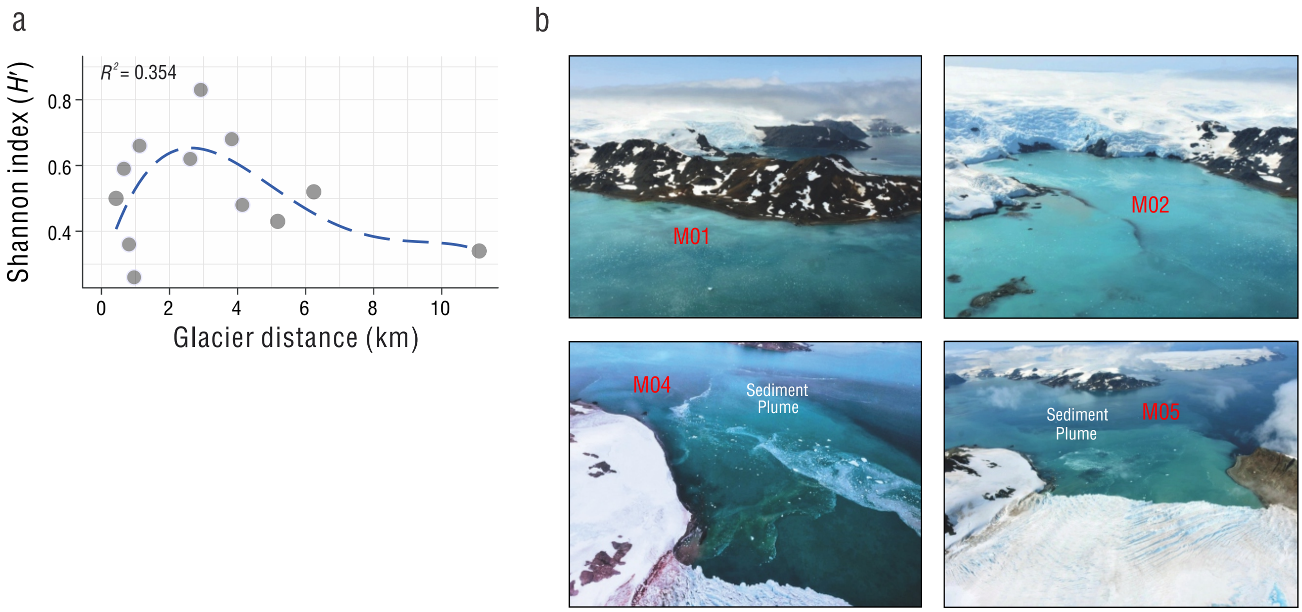

Figure 10. Influence of distance from the glacial front on phytoplankton diversity. (**a**) Relationship between the average distance from the glacier front to the stations and the average Shannon–Wiener diversity. (**b**) Aerial photographs of phytoplankton sampling stations of the internal zone: M01, M02, M04, and M05.

meltwater and stratified conditions, as has been documented in the literature (Hegseth and Von Quillfeldt 2002, von Quillfeldt 2004, Allen and Weich 2022). Furthermore, in cluster C, corresponding to stations near glaciers, the presence of *T. antarctica* is representative; this species is associated with waters adjacent to sea ice and ice shelves (Garrison 1991, Gleitz et al. 1996, Kang et al. 2001, Allen and Weich 2022). On the other hand, cluster B, which groups the stations far from the glaciers, is characterized by a greater representation of nanoflagellates, especially *L. marina*. This alga has been reported as a representative species in communities with a predominance of nanoflagellates in Bransfield Strait, Elephant Island, during different austral summers (Sánchez and Villanueva 2001, Espino et al. 2016, Ochoa et al. 2016). The relationship between the proximity of the glaciers with respect to diversity showed a polynomial behavior, where diversity gradually increased with distance until up to 3–4 km, with the exception of 2 stations with low diversity (M01 and M05). The gradual increase in diversity in the first 4 km could be caused by the nutrients and metals (bioavailable iron) released by glacier runoff that allow the proliferation of certain phytoplankton species (Arimitsu et al. 2012, Monien et al. 2017). Nutrients may also be more concentrated in inlet waters due to potential upwelling (Robakiewicz and Rakusa-Suszczewski 1999) or vertical water mixing along inlet sills (Etherington et al. 2007).

Two contrasting systems (Potter Cove and Hope Bay) on the Antarctic Peninsula show notable changes in plankton communities as a result of the effect of glacier meltwater that modifies the physicochemical and hydrological characteristics of the water column (Garcia et al. 2019). A predominant microbial food web was observed at sites near glaciers due to the decrease in salinity and stratification of the water column, which favored the development of small eukaryotic algae. Likewise, an ecological study from December 2015 to April 2016 in Andvord Bay, located in the Western Antarctic Peninsula, showed that the total abundance of phytoplankton throughout the study period positively correlated with glacier meltwater (Pan et al. 2020). Furthermore, it confirmed that flagellates may be the dominant taxon in waters near the coast of Antarctica, which is consistent with what was observed in Admiralty Bay. These changes also alter habitat conditions (increase in suspended particles and decrease in salinity) and the quality of available food (shift to small phytoplankton cells), thus affecting the structure and dynamics of micro- and mesozooplankton (Fuentes et al. 2016; Garcia et al. 2016, 2019).

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Declarations

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Conflict of interest

The authors declare no conflict of interest.

Author contributions

KM: Conceptualization; Research; Methodology; Writing-preparing the original draft; Writing (reviewing and editing). EL: Conceptualization; Research; Methodology; Writing (reviewing and editing). SRV: Data curation; Research; Formal analysis; Writing (preparing the original draft); Writing (reviewing and editing). MB: Research; Writing (reviewing and editing). PT: Acquisition of funds; Project administration; Writing (reviewing and editing).

Data availability

Data for this study can be obtained from the corresponding author upon reasonable request.

Use of AI tools

The authors did not employ any AI tools in this work.

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