



Microphytoplankton communities off the Antarctic Peninsula region in austral summer 2010/2011

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Abstract: Microphytoplankton communities in waters near the Antarctic Peninsula were investigated using collections made during two krill harvesting cruises in austral summer 2010/2011. Twenty-five net-haul samples were collected. The species composition was assessed, and the cell abundance was counted with a light microscope. A total of forty-four species were recorded, with diatoms being the most abundant group. The predominant species near the South Shetland Islands (SSIs) were *Fragilariopsis kerguelensis*, *Pseudo-nitzschia lineola* and *Thalassiothrix antarctica*, while *Rhizosolenia antennata* f. *semispina* was the most common species near the South Orkney Islands (SOIs). Habitat use was preferentially distributed. The average cell abundance of total phytoplankton was 6.6×10^{11} cells m^{-2} with high densities detected at the southwest tip of the Antarctic Peninsula. Cluster analysis clearly illustrated that the microphytoplankton communities were different at the SSIs and SOIs. Correlation analysis was applied to interpret the relationship between phytoplankton distribution and associated hydrographic conditions. Total phytoplankton abundance showed a significant negative correlation with sea surface salinity ($p < 0.01$). The results implied that the high phytoplankton biomass was supported primarily by suitable physical conditions in the upper water column, i.e., relatively stable, stratified and well-lighted seawaters. Water stability in combination with the depth of the upper mixed layer might be the main factor controlling the phytoplankton distribution in waters near the Antarctic Peninsula.

Key words: Antarctic, phytoplankton, community structure, chlorophyll *a*.

Introduction

The Southern Ocean plays a crucial role in the global marine carbon cycle and is predicted to have a large impact on oceanic CO₂ uptake and global warming (Sarmiento and Le Quéré 1996; Gille 2002). Due to the limitation of primary production caused by low concentrations of micro-nutrients such as iron, the Southern Ocean is often recognised as a high-nutrient, low-chlorophyll (HNLC) region

(Boyd *et al.* 2007). In the coastal waters of the Antarctic Peninsula and nearby islands, the levels of phytoplankton biomass are usually very high during the spring and summer seasons (Varela *et al.* 2002). Productive shelf waters provide a sufficient food source for those macrozooplankton grazers (*e.g.*, euphausiids and salps) that are considered to be crucial in the carbon flow and energy transfer of the Antarctic ecosystem (Schmidt *et al.* 2012).

The dynamics of Antarctic phytoplankton communities are affected by many factors, such as the depth of the upper mixed layer (UML), advection processes driven by the forcing of winds and storms, hydrographic fronts, the trajectory of icebergs, the recruitment of nutrients, particularly micronutrients, and grazing pressure from macrozooplankton (Smith and Nelson 1986; Orsi *et al.* 1995; Ross *et al.* 1998; Kopczyńska 2008; Cefarelli *et al.* 2011). The marginal ice zone (MIZ) is often considered a region of elevated primary productivity and phytoplankton blooms (Garrison *et al.* 1987). As the ice retreats, low-salinity melt water creates a stable environment with a shallow mixed layer and high irradiance, favouring phytoplankton growth and accumulation (Smith and Nelson 1985; Garibotti *et al.* 2005). Additional benefits might come from the release of essential micronutrients from the melting ice (Lannuzel *et al.* 2007).

Phytoplankton forms the base of the classic food chain (phytoplankton-krill-top predators) in the Antarctic ecosystem. Previous studies indicated that phytoplankton community composition was characterised by *Chaetoceros*, *Fragilariopsis*, *Pseudo-nitzschia* and *Rhizosolenia* species groups in the Antarctic Zone, *e.g.*, the Weddell Sea (Fryxell 1989; Estrada and Delgado 1990; Ligowski and Kopczyńska 1991; Kang and Fryxell 1993; Savidge *et al.* 1995) and the Indian sector of the Antarctic Ocean (Kopczynska *et al.* 1986). Investigations in open waters of the Southern Ocean north of the South Shetland Islands (SSIs) and South Orkney Islands (SOIs) have been poorly documented (Economou-Amilli 1998). In this study, the characteristics of microphytoplankton (*e.g.*, diatoms and dinoflagellates) was studied in waters adjoining the Antarctic Peninsula during austral summer 2010/2011. This work may be informative for krill harvesting near Antarctica.

The objectives of this study were: (1) to assess the cell abundance and species composition of microphytoplankton communities in waters adjoining the Antarctic Peninsula, (2) to assess the spatial distribution of dominant species relative to preferred habitats, and (3) to indicate the potential environment drivers affecting phytoplankton distribution in the surveyed waters.

Materials and methods

Cruise track. — Samples used in this study were collected during two krill harvesting cruises conducted in the Southern Ocean adjacent to the Antarctic Pen-

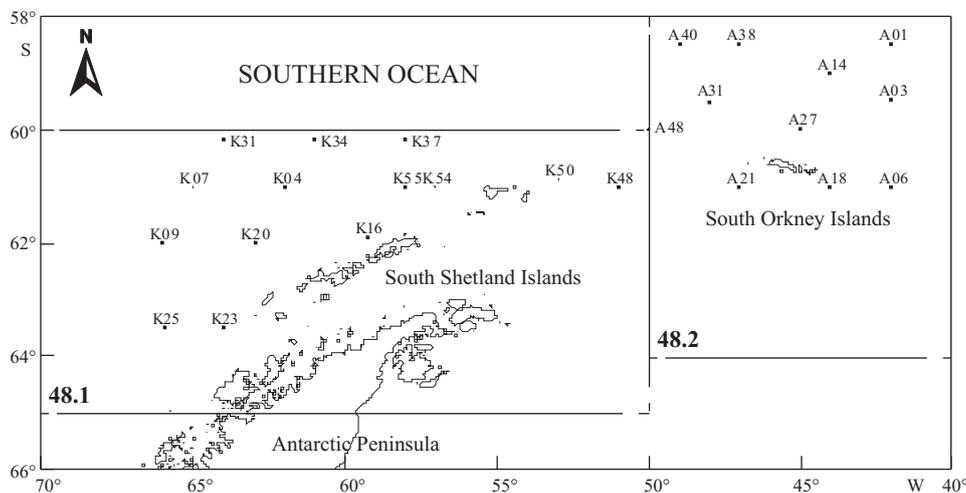


Fig. 1. Map showing the sampling stations in the Southern Ocean adjacent to the Antarctic Peninsula (48.1 and 48.2 indicate the Subareas of the FAO Major Fishing Area 48).

insula, the South Shetland Islands (SSIs) and the South Orkney Islands (SOIs), corresponding to CCAMLR and FAO Sub-areas no-s. 48.1 and 48.2 (Fig. 1). The first cruise (from 17th to 25th December 2010) was undertaken on R/V *Kaixin*, in waters adjoining the Antarctic Peninsula and the SSIs (Subarea 48.1). The second cruise (from 4th to 28th February 2011) was performed by R/V *Anxinghai*, and surveyed the waters neighbouring the SOIs (Subarea 48.2). A total of 25 sampling stations were established for studying net-phytoplankton and hydrographic parameters, with 14 stations (from K04 to K55) sampled on the first cruise and 11 stations (from A01 to A48) sampled on the second cruise.

Field sampling. — Net-phytoplankton samples were collected with a standard net III (mesh size 76 μm , simple conical tow net), which is a standard phytoplankton tool used in China. A vertical haul was made at each station from 200 m depth to the surface. These samples were preserved in 0.5 L polyethylene bottles with neutralised formalin (final concentration 5%). Water samples for chlorophyll *a* (Chl *a*) determination were collected by deploying a rosette Sea-Bird CTD (Conductivity, Temperature, Depth) sampler equipped with twelve 5 L Go-Flo bottles. Seawater temperature and salinity were recorded using the onboard real-time CTD facility.

Laboratory analysis. — In the onboard laboratory, measurements of Chl *a* were made by filtration of 0.5 L seawater through Whatman GF/F filters, extraction in 90% acetone for 24 h (dark, 4°C) and determination of fluorescence (after Welschmeyer 1994) using a Turner Designs Trilogy (CHL NA, Model # 046) calibrated with pure Chl *a* standards (Sigma, UK). MODIS/AQUA chlorophyll val-

ues, averaged monthly over the duration of the surveys (December 2010–February 2011), were obtained from the NASA ocean colour server (<http://oceancolor.gsfc.nasa.gov/>).

At the onshore laboratory, phytoplankton species were identified and counted under a Leica Biomed (type 020-507.010) light microscope (N.A. 0.65) in a 0.5 mL phytoplankton counting chamber (similar to a Sedgwick-Rafter chamber). Phytoplankton taxonomy was determined according to species morphological differences (Priddle and Fryxell 1985; Medlin and Priddle 1990; Hasle and Syvertsen 1997).

Data analysis. — Four indices of phytoplankton community structure were calculated: species richness (d_{Ma} , Margalef 1958), species diversity (H' , Shannon and Weaver 1949), species evenness (J , Pielou 1969) and the dominance index (Y , Dufrene and Legendre 1997). The formula used to calculate the Shannon Index was:

$$H' = -\sum_{i=1}^S P_i \times \log_2 P_i$$

where S is the number of species and P_i is the relative species abundance.

Phytoplankton community similarity was determined by cluster analysis with the unweighted pair-group method with arithmetic means (UPGMA) using the MVSP 3.13n software. Whittaker's index of percent similarity (PS) was calculated from the percent cell abundance for each species (Whittaker 1952).

Pearson's correlation analysis was used to test the simple relationship between phytoplankton distribution and environmental factors. Correlation coefficients and their significance were determined using the IBM SPSS Statistics 20 software following a $\log_{10}(x+1)$ -transformation of the initial data.

Results

Hydrographic conditions. — During the first cruise in early summer, the sea surface temperature (SST) varied between -0.18°C and 1.48°C , averaging $0.52 \pm 0.49^{\circ}\text{C}$; the three stations (K48, K09 and K07) recorded temperatures below zero. Sea surface salinity (SSS) ranged from 33.8 to 34.5, averaging 33.9 ± 0.2 (Fig. 2). During the second summer cruise, the SST increased significantly, reaching an average temperature of $2.01 \pm 0.56^{\circ}\text{C}$, with a range from 1.14°C to 2.84°C . The SSS remained steady at 34.1 ± 0.1 , ranging from 33.9 to 34.3.

Chlorophyll *a*. — In early summer, surface Chl *a* varied between $0.05 \mu\text{g L}^{-1}$ and $0.44 \mu\text{g L}^{-1}$, with an average of $0.19 \pm 0.12 \mu\text{g L}^{-1}$. Chl *a* gradually increased to an average concentration of $0.37 \pm 0.12 \mu\text{g L}^{-1}$, with the minimum and maximum values of $0.13 \mu\text{g L}^{-1}$ and $0.71 \mu\text{g L}^{-1}$, respectively (Fig. 3). Satellite-derived Chl *a* during the survey time period showed similar distribution patterns. Phytoplankton biomass was high in waters surrounding the SSIs and SOIs in comparison with

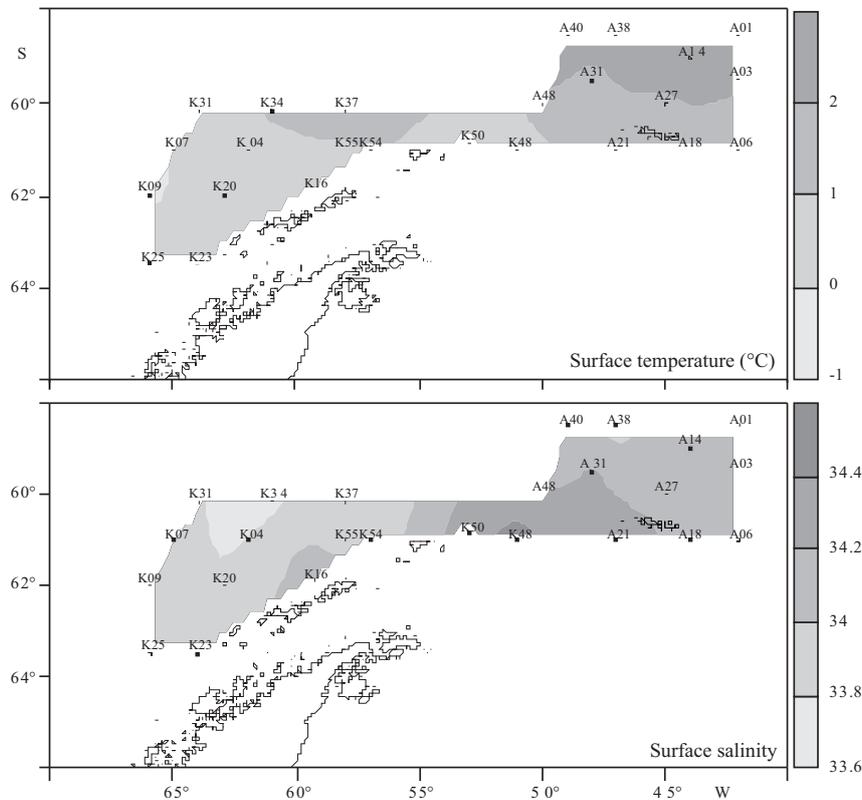


Fig. 2. Distribution of sea surface temperature and salinity.

open waters. The surface Chl *a* concentration was positively correlated with SST and negatively correlated with SSS, but neither correlation was significant.

Cell abundance. — Total phytoplankton cell abundance ranged from a minimum of 1×10^6 cells m^{-2} at A21 to a maximum of 7.1×10^{12} cells m^{-2} at K25, with an average of 6.6×10^{11} cells m^{-2} . Phytoplankton densities were high in the western area of the Antarctic Peninsula (Fig. 4). Average cell abundance in waters adjoining the SSIs (9.8×10^{11} cells m^{-2}) was nearly four times greater than the region adjoining the SOIs (2.5×10^{11} cells m^{-2}). Diatom abundance accounted for 92%, on average, of the total phytoplankton abundance. Diatoms had an average of 6.5×10^{11} cells m^{-2} , with the highest value detected at K25. In contrast, dinoflagellate cell abundance was relatively low in the survey areas, with an average of 7×10^9 cells m^{-2} and 2.6×10^9 cells m^{-2} in the waters of the SSIs and SOIs, respectively.

Species composition and abundance. — A total of forty-four species were identified from the samples collected during the two cruises (Table 1). Diatoms were the most abundant group, represented by thirty-seven species. Other groups, such as dinoflagellates, prymnesiophytes and silicoflagellates were found at low

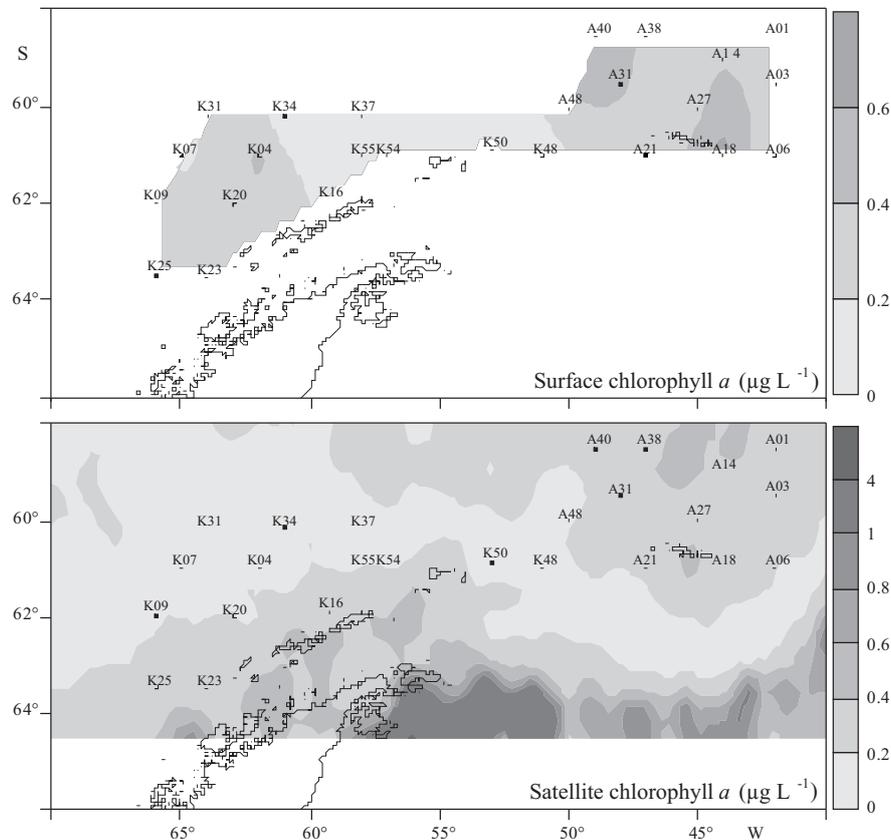


Fig. 3. Distribution of sea surface chlorophyll *a*.

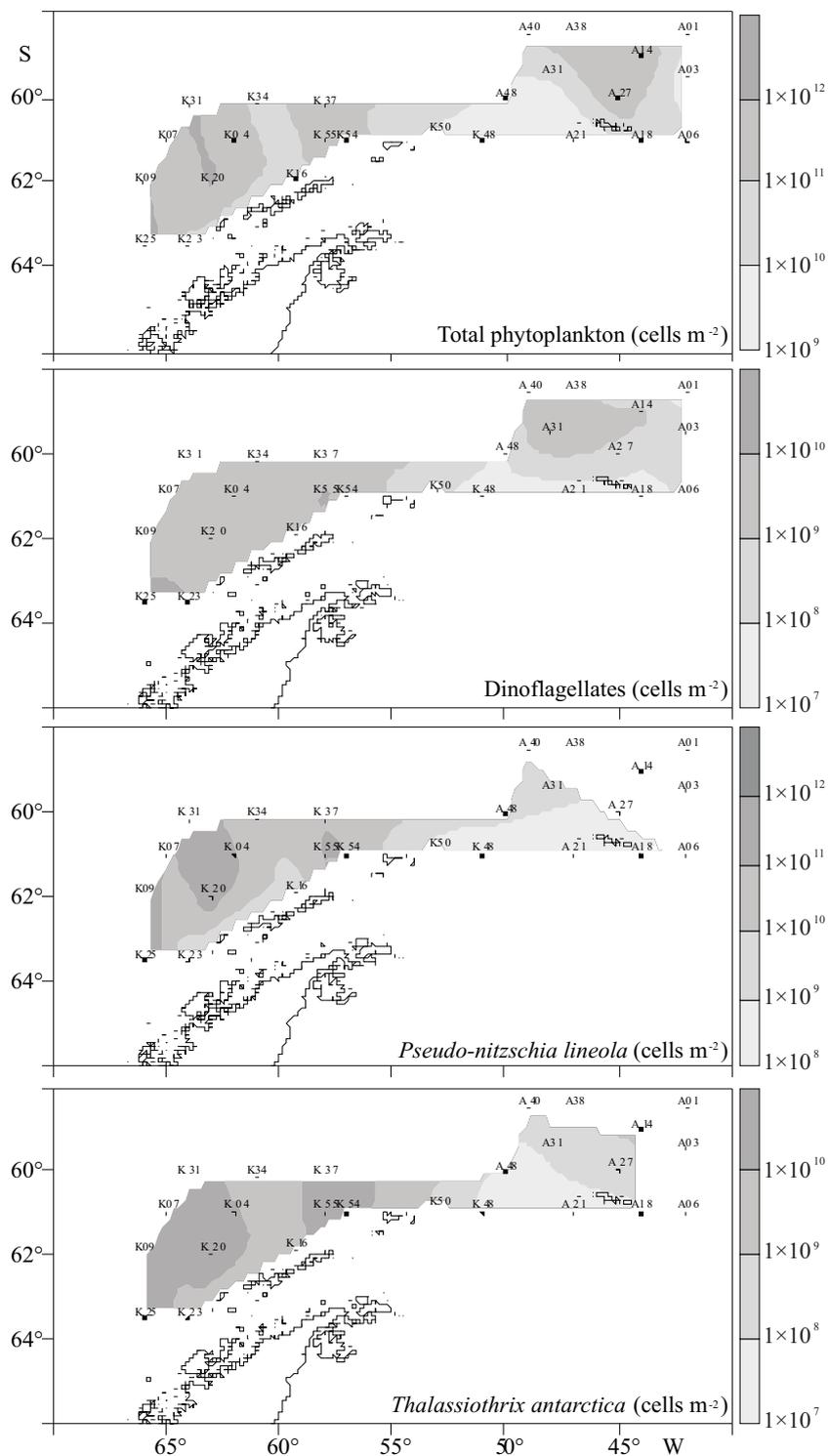
frequencies. The predominant diatom forms were from the genus *Rhizosolenia* and *Chaetoceros* (Bacillariophyceae), with seven and five species, respectively. In general, phytoplankton from the Antarctic Peninsula and the adjacent Southern Ocean was characterised by endemic and cosmopolitan species. Few samples contained polar or cold-water species. According to the dominance index, four species dominated the microphytoplankton communities during the two cruises. These species were *Fragilariopsis kerguelensis* (O'Meara) Hustedt, *Pseudo-nitzschia lineola* (Cleve) Hasle, *Rhizosolenia antennata* f. *semispina* Sundström and *Thalassiothrix antarctica* Schimper ex Karsten, with dominance indices of 0.22, 0.20, 0.16 and 0.02, respectively; each of these species thrived in the SSIs region (Fig. 4). However, in waters adjoining the SOIs, only *R. antennata* f. *semispina* was found at high cell densities. The average abundance of the four dominant species in the waters of the SSIs (K04–K55) were 3.7×10^{11} cells m^{-2} , 3.6×10^{11} cells m^{-2} , 2×10^{10} cells m^{-2} and 3.6×10^{10} cells m^{-2} , with maximum counts of 3.2×10^{12} cells m^{-2} , 2.8×10^{12} cells m^{-2} , 6.6×10^{10} cells m^{-2} and 9.4×10^{10} cells m^{-2} , respectively. Abundance for all SSIs dominant species peaked at K25. The mean density of *R.*

Table 1

List of phytoplankton species recorded during the study period.

Diatoms
<i>Actinocyclus actinochilus</i> (Ehrenberg) Simonsen
<i>Asteromphalus hookeri</i> Ehrenberg
<i>Chaetoceros atlanticus</i> Cleve
<i>C. criophilus</i> Castracane
<i>C. curvisetus</i> Cleve
<i>C. dichæta</i> Ehrenberg
<i>Chaetoceros</i> sp.
<i>Corethron inerme</i> Karsten
<i>C. pennatum</i> (Grunow) Ostenfeld
<i>Coscinodiscus oculus-iridis</i> Ehrenberg
<i>C. radiatus</i> Ehrenberg
<i>Coscinodiscus</i> sp.
<i>Dactyliosolen antarcticus</i> Castracane
<i>Eucampia antarctica</i> (Castracane) Mangin
<i>Fragilariopsis curta</i> (van Heurck) Hustedt
<i>F. kerguelensis</i> (O'Meara) Hustedt*
<i>F. rhombica</i> (O'Meara) Hustedt
<i>Leptocylindrus mediterraneus</i> (Peragallo) Hasle
<i>Navicula directa</i> (W. Smith) Ralfs
<i>Odontella weissflogii</i> (Janisch) Grunow
<i>Pleurosigma directum</i> Grunow
<i>Proboscia alata</i> (Brightwell) Sundström
<i>P. inermis</i> (Castracane) Jordan <i>et</i> Ligowski
<i>P. truncata</i> (Karsten) Nöthig <i>et</i> Ligowski
<i>Pseudo-nitzschia heimii</i> Manguin
<i>P. lineola</i> (Cleve) Hasle*
<i>Rhizosolenia antennata</i> (Ehrenberg) N.E. Brown
<i>R. antennata</i> f. <i>semispina</i> Sundström*
<i>R. chunii</i> Karsten
<i>R. cylindrus</i> Cleve
<i>R. simplex</i> Karsten
<i>R. styliformis</i> Brightwell
<i>R. styliformis</i> var. <i>longispina</i> Hustedt
<i>Thalassionema nitzschioides</i> (Grunow) Mereschkowsky
<i>Thalassiosira antarctica</i> Comber
<i>T. gracilis</i> (Karsten) Hustedt
<i>Thalassiothrix antarctica</i> Schimper <i>ex</i> Karsten*
Dinoflagellates
<i>Gymnodinium</i> sp.
<i>Oxytoxum longiceps</i> Schiller
<i>Protoperidinium antarcticum</i> (Schimper <i>ex</i> Karsten) Balech
<i>Protoperidinium</i> sp.
<i>Pyrophacus steinii</i> (Schiller) Wall <i>et</i> Dale
Prymnesiophytes
<i>Phaeocystis antarctica</i> Karsten
Silicoflagellates
<i>Dictyocha speculum</i> Ehrenberg

*indicates the dominant phytoplankton species identified during the study period.



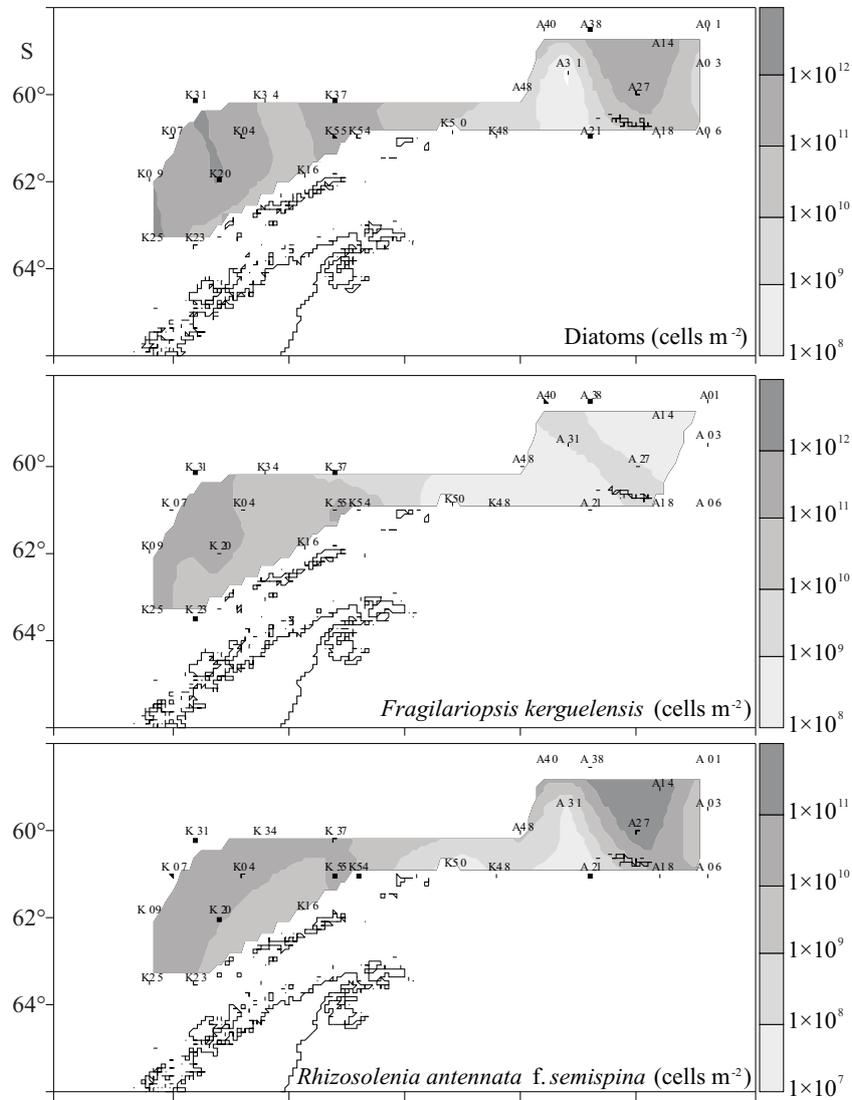


Fig. 4. Distribution of phytoplankton cell abundance in the study area.

antennata f. *semispina* near the SOIs (A01–A48) was 2.3×10^{11} cells m^{-2} , with the highest value of 8.9×10^{11} cells m^{-2} recorded in A14. During the survey, several other species were also present at relatively high abundance, including *Chaetoceros criophilus* Castracane, *F. curta* (van Heurck) Hustedt, *Thalassiosira antarctica* Comber and *Corethron inerme* Karsten. However, no other dinoflagellates were found dominating the microphytoplankton communities in this study.

Community diversity. — Margalef's index, the Shannon-Weaver index and Pielou's index were used to evaluate the species richness, species diversity and

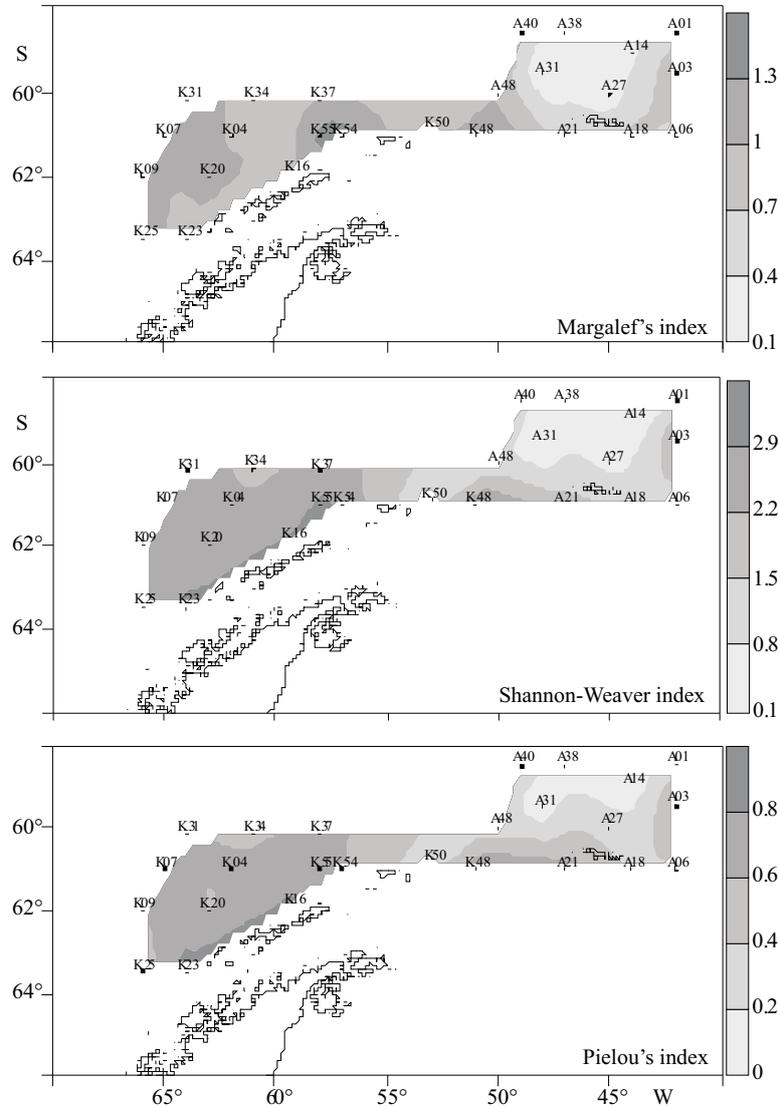


Fig. 5. Distribution of phytoplankton diversity indices in the study area.

species evenness of the phytoplankton community (Fig. 5). The means of d_{Ma} , H' and J around the SSIs (1.12, 2.53 and 0.64, respectively) were clearly higher than those calculated for the SOIs region (0.55, 0.97 and 0.33, respectively). Interestingly, sampling stations with low phytoplankton diversities were usually dominated by only one species with extremely high cell abundance. For example, *R. antennata* f. *semispina* accounted for 98.4% and 97.3% of total phytoplankton abundance at stations A14 and A38, respectively, although there were fairly low community diversities at these two stations.

Discussion

The regions surveyed in this study are characterised by diverse water masses and frontal structures, accompanied by complex patterns of water circulation (Hofmann *et al.* 1992; Garabato *et al.* 2002; Pollard *et al.* 2002). The vast, cold waters of the Antarctic Circumpolar Current (ACC) transfer mass and heat between major ocean basins and play an essential role in the redistribution of salt, nutrients and heat (Smith *et al.* 2010). Diatom-dominated phytoplankton communities have been associated with the intrusion and upwelling of the Upper Circumpolar Deep Water (UCDW) into the shelf waters of the West Antarctic Peninsula (WAP) region (Prézelin *et al.* 2000). Mesoscale blooms have frequently been observed in the marginal ice zone where the melting of sea-ice stabilises the surface water and confines the phytoplankton to the euphotic zone by vertical stratification (Lancelot *et al.* 1993). Consequently, the variability of primary production along the WAP shelf is related to the amount of open water within the annual ice pack, in conjunction with the upper mixed layer (Ducklow *et al.* 2006; Vernet *et al.* 2008).

The on-going regional climate change along the WAP has significantly altered phytoplankton biomass and size structure in recent decades. Summertime surface Chl *a* has declined by 12% in the WAP region over the past 30 years, with the largest decreases equator-ward, but with substantial increases occurring farther south (Montes-Hugo *et al.* 2009). The contribution of 'small' phytoplankton (< 20 µm) has increased in the last decade in WAP waters (Montes-Hugo *et al.* 2008). Minute phytoflagellates, ultraplanktonic flagellates and cryptophytes (*Cryptomonas* spp.) were documented as dominant groups in the WAP phytoplankton (Rodríguez *et al.* 2002; Garibotti *et al.* 2005). Species diversity of phytoplankton around the tip of the Antarctic Peninsula depicted clear spatial patterns. In coastal waters, the communities were generally dominated by diatoms, whereas nanoflagellates, such as cryptophytes and/or *Phaeocystis antarctica*, frequently occurred in open-ocean areas. In addition, autotrophic dinoflagellates (*Gymnodinium* spp.) also contributed significantly to total Chl *a* biomass in some well-stratified waters (Savidge *et al.* 1995; Mendes *et al.* 2012).

In the present study, high cell abundance was recorded in the southwestern portion of the SSIs region. It is noteworthy that the highest cell abundance, recorded at K25, was almost five times greater than that of the second-highest sampling station K31. Vertical profiles of temperature and salinity demonstrated that the water columns were well stratified at K25 and K31 (Fig. 6). However, strong vertical mixing of seawater was found in the upper water column at K48. Thus, the extremely high phytoplankton biomass at K25 might be due to the relatively stable upper water column created by the water stratification, as well as to the shallow UML (< 80 m), which enabled the light irradiance of phytoplankton thus favouring growth and cell accumulation. In contrast, phytoplankton abundance was lower in

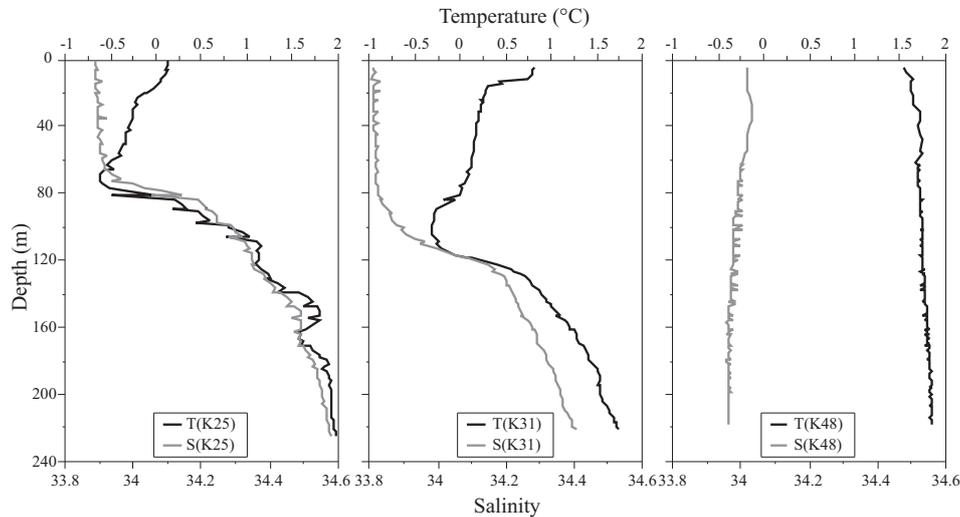


Fig. 6. Vertical profiles of seawater temperature and salinity at specific sampling stations.

unstable, non-stratified and deep UML seawaters (*e.g.*, K48) where light might be the limiting factor.

During the surveys, sea surface temperature and salinity clearly distinguished the regions around the SSIs and SOIs. Surface temperatures increased northward, while surface salinity was elevated in the Weddell-Scotia Confluence area. To test the similarities of phytoplankton communities within the survey area, a cluster analysis was carried out among the sampling stations under different hydrographic conditions. Two major clusters were identified based on percent similarity (Fig. 7), coinciding with the geographic locations of sampling. Cluster I (ten label-A stations plus K50) and Cluster II (thirteen label-K stations plus A40) were representative of phytoplankton groups around the SOIs and SSIs, respectively. Phytoplankton communities that were similar in species composition and cell abundance among sampling stations typically had close linkages in the dendrogram. However, this was not the case when considering major clustered groups with low percent similarities. Phytoplankton communities near the SSIs were dominated by *Fragilariopsis kerguelensis* and *Pseudo-nitzschia lineola*. In contrast, the dominant species near the SOIs were *Rhizosolenia antennata* f. *semispina* and *Corethron inerme*. The differences in phytoplankton composition between these two regions could be related to various physico-chemical parameters and biological removal processes (Kang *et al.* 2001). Long chain-forming and large-celled diatoms were common phytoplankton species in the open, iron-limited waters of the ACC, which contributed greatly to the bulk of diatomaceous ooze accumulating in sediments (Grigorov *et al.* 2002).

Correlation analysis was used to examine the relationship between phytoplankton distributions and associated hydrographic conditions (Table 2). No statistical relationship was found between cell abundance and SST. However, total

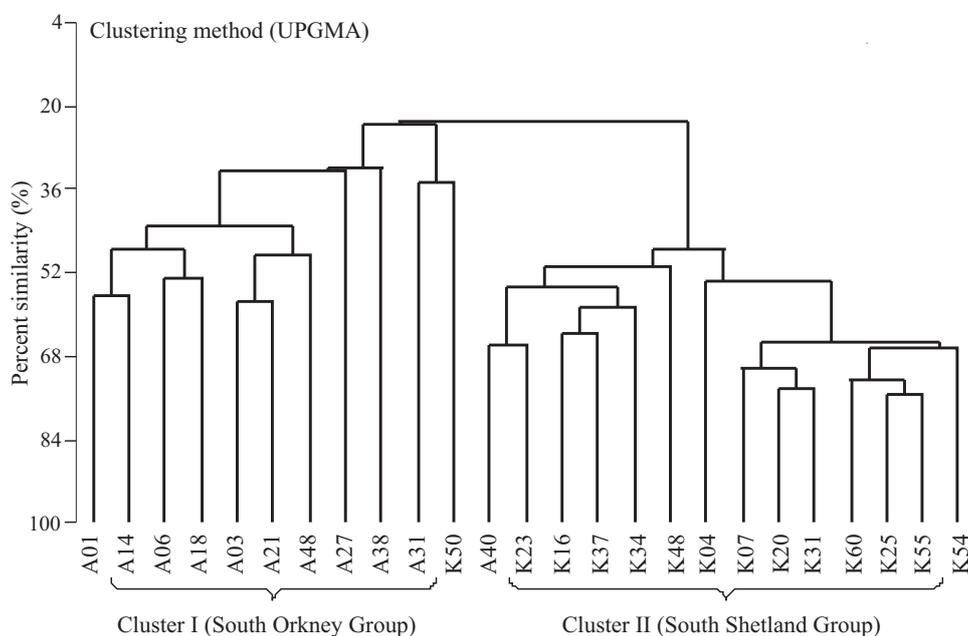


Fig. 7. Dendrogram showing the percent similarity of phytoplankton composition at the sampling stations (UPGMA: unweighted pair-group method with arithmetic means).

phytoplankton abundance showed a significant negative correlation with SSS (Pearson's $r = -0.763$, $p < 0.01$, $n = 25$). Moreover, the distribution of diatoms, dinoflagellates and dominant species seemed to be dramatically influenced by SSS. An 18-year summertime phytoplankton survey in the SSIs indicated that Chl *a* exhibited a spatially consistent unimodal distribution across surface salinities (Hewes *et al.* 2009), with the highest Chl *a* concentrations detected at intermediate

Table 2
Pearson correlation of phytoplankton abundance with sea surface temperature (SST) and sea surface salinity (SSS).

Phytoplankton	SST	SSS
Sea surface chlorophyll <i>a</i> ($\mu\text{g L}^{-1}$)	0.377	-0.048
Total phytoplankton (cells m^{-2})	-0.163	-0.763*
Diatoms (cells m^{-2})	-0.196	-0.739*
Dinoflagellates (cells m^{-2})	-0.224	-0.624*
<i>Fragilariopsis kerguelensis</i> (cells m^{-2})	-0.303	-0.769*
<i>Pseudo-nitzschia lineola</i> (cells m^{-2})	-0.066	-0.732*
<i>Rhizosolenia antennata</i> f. <i>semispina</i> (cells m^{-2})	0.216	-0.634*
<i>Thalassiothrix antarctica</i> (cells m^{-2})	-0.301	-0.761*

*correlation is significant at the 0.01 level.

salinities (~34) corresponding to areas with shallow UML (~40 m). This finding is in accord with the results of the current study, which showed that higher densities of phytoplankton dwelled in the southwestern waters of the SSIs where there were relatively lower surface salinities and a shallow UML.

In this paper, we used quantitative and qualitative methods to assess the microphytoplankton communities in waters surrounding both the South Shetland and South Orkney Islands. A conspicuous difference was found in the community structure and species diversity between the two regions. We also found that the dominant species, such as *Fragilariopsis kerguelensis*, *Pseudo-nitzschia lineola*, *Rhizolenia antennata* f. *semispina* and *Thalassiothrix antarctica*, exhibited preferential habitat distributions. These species were found at high cell densities in the stable, stratified and well-lighted upper seawaters with relatively low salinity and temperature. Thus, the high phytoplankton biomass at some productive stations near the SSIs was supported primarily by the suitable physical conditions of the upper water column. In summary, the stability of seawaters, in combination with the depth of the UML, might be the main factor controlling phytoplankton distribution in waters adjoining the Antarctic Peninsula.

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