

1 **Impact of sea ice on the structure of phytoplankton**
2 **communities in the northern Antarctic Peninsula**

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1 **Abstract**

2 The seasonal advance and retreat of sea ice around the northern Antarctic
3 Peninsula can have a significant impact on phytoplankton, mainly due to
4 alterations in the availability of ice-free areas, micro-nutrient inputs by meltwater
5 and variations in water column structure. The aim of this work was to evaluate
6 the effect of sea ice conditions on phytoplankton biomass and community
7 composition in an area off the northern Antarctic Peninsula, a region undergoing
8 important warming processes. In two consecutive summer cruises (2013 and
9 2014), seawater samples were analysed for nutrients and phytoplankton
10 (through HPLC-CHEMTAX approach), and measurements were made for water
11 column physical structure evaluation. Two contrasting conditions were studied:
12 a strong environmental gradient around the sea ice edge, with a marked
13 meltwater signal (summer 2013) and the same area with little indication of
14 meltwater and no detectable sea ice conditions (summer 2014). In the first year,
15 the phytoplankton communities were massively dominated by nanoflagellates
16 such as cryptophytes, small dinoflagellates and *Phaeocystis antarctica*, but with
17 differences between stations with less influence of meltwater (dominance of
18 dinoflagellates type B, mainly *Gymnodinium* spp., mean chlorophyll *a* = 1.37 mg
19 m⁻³) and stations closer to the sea ice edge (dominance of cryptophytes, mean
20 chlorophyll *a* = 0.98 mg m⁻³). In the second year, cryptophytes were apparently
21 replaced by diatoms type B (mainly *Pseudonitzschia* spp., 24% contribution,
22 mean chlorophyll *a* = 0.93 mg m⁻³), although dinoflagellates were also
23 important. Therefore, there was a clear distinction between the phytoplankton
24 communities under sea ice influence, where mainly cryptophytes were
25 associated with shallow mixed layers and high water column stability in 2013
26 and an important presence of diatoms in 2014, associated with deeper mixed
27 layers, lower silicic acid concentrations and higher magnitudes of both salinity
28 and temperature, under very little sea ice influence. Gymnodinioid
29 dinoflagellates were an important component in both years, apparently
30 occupying sites/conditions less favourable to cryptophytes. These results
31 support previous suggestions that climate factors leading to shortening of the
32 sea ice season in the region do have an important impact particularly in shaping
33 the dominance of the main phytoplankton functional groups in the region.

34 **Keywords:** Antarctic Peninsula, sea ice, phytoplankton, HPLC pigments,
35 CHEMTAX, cryptophytes, peridinin-lacking autotrophic dinoflagellates.

1 **1. Introduction**

2 The Antarctic Peninsula (AP) is experiencing one of the fastest warming
3 rates on Earth, with an increase in the mean atmospheric temperature of 2°C
4 (6°C in winter; > 5× the global average) since 1950 (Ducklow et al., 2007).
5 Along with atmospheric and ocean surface warming in the region (Meredith and
6 King, 2005), increased heat due to intrusions of warm mid-depth Upper
7 Circumpolar Deep Water from the Antarctic Circumpolar Current onto the
8 continental shelf (Moffat et al., 2009; Couto et al., 2017) has caused a 0.6°C
9 increase in temperature of the upper 300 m of the water column (Meredith and
10 King, 2005; Martinson and McKee, 2012; Turner et al., 2014). Consequently,
11 87% of the AP glaciers are in retreat, the annual sea ice season has shortened
12 by 90 days, and perennial ice is no longer a feature of the northern AP (Cook et
13 al., 2005; Martinson et al., 2008; Stammerjohn et al., 2008; Peck et al., 2010;
14 Cook et al., 2016).

15 The Southern Ocean is generally a high-nutrient and low-chlorophyll
16 (HNLC) area due to limitation of primary production by low concentrations of
17 micronutrients, mainly iron (Boyd et al., 2007), light limitation through deep
18 mixing (Mitchell and Holm-Hansen, 1991; Nelson and Smith, 1991), and/or
19 grazing (Dubischar and Bathmann, 1997; Smetacek et al., 2004). However,
20 high phytoplankton biomass has been observed in particular regions, especially
21 at ocean frontal systems, marginal ice zones and nearshore straits, bays, and
22 lees of islands (Prézelin et al., 2000 and references therein). Phytoplankton
23 blooms in those regions, normally dominated by diatoms or haptophytes, such
24 as *Phaeocystis antarctica*, are generally associated with the development of a

1 shallow mixed layer and/or iron availability (Smith and Nelson, 1986; Prézelin et
2 al., 2000).

3 The Antarctic sea ice zone constitutes, through seasonal sea ice retreat
4 and advance, a key component of the Southern Ocean dynamics, with regards
5 to both energy transfer between atmosphere and ocean and food-web
6 dynamics (Deppeler and Davidson, 2017). In the AP region, meltwater
7 conditions are likely to become more prevalent in surface waters because of the
8 warming trend in the area (Dierssen et al., 2002; Moline et al., 2004).

9 In the areas around the AP, decreased salinity levels have been
10 associated with a transition from a diatom-dominated system to one dominated
11 by smaller cryptophytes (Moline et al., 2004; Montes-Hugo et al., 2009; Mendes
12 et al., 2013, 2017). As diatoms are more efficiently grazed by Antarctic krill than
13 cryptophytes, this shift may affect food web trophic interactions (Haberman et
14 al., 2003). Since phytoplankton supports oceanic food webs and plays a key
15 role on the AP marine ecosystem's resilience, changes in the abundance and
16 composition of phytoplankton groups may have a direct effect on the whole
17 regional ecosystem. Therefore, studies on the influence of environmental
18 constraints upon species/groups composition are relevant to evaluate potential
19 ecosystem changes, both at short and long-term scales.

20 Studies of phytoplankton community through chemotaxonomic methods
21 based on High Performance Liquid Chromatography (HPLC) pigment analysis
22 (e.g. Mendes et al., 2015) rely on the relative concentration of pigments that are
23 characteristic of distinct algal taxonomic groups (Wright and Jeffrey, 2006;
24 Higgins et al., 2011). A common approach involves using the software
25 CHEMTAX (CHEMical TAXonomy) on HPLC pigment ratios signatures (Mackey

1 et al., 1996) to determine the relative contribution of phytoplankton groups to
2 total biomass. The HPLC-CHEMTAX approach has been extensively and
3 successfully used in many worldwide investigations (e.g. Wright et al., 2010;
4 Schlütter et al., 2011; Mendes et al., 2011; 2015; Araujo et al., 2017), including
5 in the AP (Rodriguez et al., 2002; Kozłowski et al., 2011; Mendes et al., 2012),
6 to determine the distribution and biomass of phytoplankton functional groups.
7 This approach provides valuable information about the whole phytoplankton
8 community, including small-size species, which are normally difficult to identify
9 by light microscopy.

10 The present work evaluates phytoplankton community changes during
11 two consecutive late-summer oceanographic surveys (February 2013 and 2014)
12 conducted in the same region at the Weddell-Scotia Confluence zone, under
13 contrasting sea ice situations: the first year was strongly influenced by the
14 presence of sea ice, while in the second sampling year there was practically no
15 sea ice melting condition. In this context, the study aims to address the impact
16 of sea ice processes on the in situ structure of phytoplankton communities, at
17 both horizontal and vertical (0–100m) scales, at that area of the northern
18 Antarctic Peninsula (NAP).

19

20 **2. Material and methods**

21

22 2.1. Environmental context and cruise design

23 The data set in this work was collected during two oceanographic cruises
24 conducted on board the *RV Almirante Maximiano* of the Brazilian Navy in the
25 northwestern Weddell Sea (Fig. 1), during late summers of 2013 (25 February

1 to 01 March; 34 stations) and 2014 (23–24 February; 15 stations). The study
2 region is located near the tip of the Antarctic Peninsula, with the Clarence Island
3 to the southwest, the Powell Basin/Weddell Sea to the southeast and the Scotia
4 Sea to the north (Fig. 1). This region is part of the Weddell-Scotia Confluence
5 (WSC; Patterson and Sievers, 1980), where surface/intermediate waters from
6 the Weddell and Scotia seas merge.

7 In February 2013, particularly, the development of a high-pressure
8 system over the Antarctic Peninsula intensified the cold, southerly winds, which
9 advected and apparently agglomerated together a great amount of sea ice
10 northwards (<http://nsidc.org/arcticseaicenews/2013/02/>). That particular
11 scenario contributed to the higher than average sea ice concentration in that
12 region during the first sampling period, which did not occur in the following year.
13 Thus, the 2013 station grid comprised an area further northward than expected.
14 However, the well-defined sea ice boundary allowed the accomplishment of the
15 proposed project goals. Therefore, the sampling strategy was then defined,
16 taking into account the position of the sea ice boundary. The stations along the
17 longitudinal transects were conducted at 10 nm intervals, with closer intervals (~
18 1 nm) approaching the sea ice border and further south (see Fig. 1). The
19 sampling was conducted from the sea ice boundary northward and from west to
20 east. In the following year, due to time limitation and no anomalous sea ice
21 distribution in the region, some of the previous stations were reoccupied from
22 north to south, allowing investigation of the phytoplankton community
23 distribution in the study region with (2013) and without (2014) the sea ice
24 effects.

1

2 2.2. Sampling collection

3 Hydrographic data (temperature and salinity) and water samples were
4 collected using a combined Sea-Bird CTD/Carrousel 911+system[®] equipped
5 with 24 five-litre Niskin bottles. Surface water samples were taken in all CTD
6 (conductivity–temperature–depth) stations for both dissolved nutrients and
7 phytoplankton pigments analyses (Fig. 1). At some stations, chosen based on
8 the downcast fluorescence profiles (WetLabs[®] profiling fluorometer), seawater
9 samples were taken from several depths (between the surface and 100 m) to
10 characterize the vertical distribution of phytoplankton communities. However,
11 due to the absence of deep chlorophyll maximum (DCM) layers, seawater
12 samples at these selected stations were generally collected at regular depths:
13 5, 15, 25, 50, 75 and 100 m.

14

15 2.3. Water column stability/stratification parameters

16 The potential density (ρ , kg m⁻³) was calculated based on temperature,
17 salinity and pressure data in order to evaluate the physical structure of water
18 column. The upper mixed layer depth (UMLD) was determined based on
19 density profiles, according to the criteria established by de Boyer Montégut et
20 al. (2004), i.e., the depth at which potential density deviate from its 10 m depth
21 value by a threshold of $\Delta\rho = 0.03$ kg m⁻³. The water column stability (E ;
22 hereafter referred to as stability) was estimated using vertical density variations,
23 as function of the buoyancy or the Brunt-Väisälä frequency (N^2), which is
24 determined by:

1
$$N^2 = - \frac{g}{\rho} \frac{\partial \rho}{\partial z} (\text{rad}^2 \text{s}^{-2})$$

2 where g is gravity and ρ is the potential density of seawater. Stability was
3 further estimated from:

4
$$E = \frac{N^2}{g} (10^{-6} \text{ rad}^2 \text{ m}^{-1})$$

5 Average stability values (between 0 and 100 m depth) were used in the
6 statistical analyses.

7

8 2.4. Meltwater percentage estimation

9 To evaluate the effects of sea ice melting on the structure of
10 phytoplankton communities, following Rivaro et al. (2014), we calculated the
11 meltwater percentage (MW%), as the difference between the salinity measured,
12 on the same station, at surface (S_{meas}) and at a greater depth (S_{deep} ; i.e., at 300
13 m), which was presumably not influenced by sea ice dilution, assuming an
14 average sea ice salinity of 6 (Ackley et al. 1979):

15
$$MW\% = \left(1 - \frac{S_{\text{meas}} - 6}{S_{\text{deep}} - 6} \right) \times 100$$

16

17 2.5. Nutrient analysis

18 Surface seawater samples were filtered through cellulose acetate
19 membrane filters to determine dissolved inorganic nutrients (DIN: nitrate, nitrite
20 and ammonium; phosphate and silicic acid). Nutrients were analysed onboard
21 using a FEMTO® spectrophotometer, following the analytical recommendations
22 in Aminot and Chaussepied (1983). Orthophosphate was measured by reaction

1 with ammonium molybdate, with absorption readings at 885 nm. Silicic acid
2 measurements, in the form of reactive Si, were corrected for sea salt
3 interference.

4

5 2.6. HPLC pigment analysis

6 For phytoplankton pigment analysis, seawater samples (0.5–2.5 L) were
7 filtered under low vacuum through GF/F filters and these were immediately
8 frozen in liquid nitrogen for later HPLC pigment analysis. In the laboratory, the
9 filters were placed in a screw-cap centrifuge tube with 3 mL of 95% cold-
10 buffered methanol (2% ammonium acetate) containing 0.05 mg L⁻¹ trans-β-apo-
11 8'-carotenal (Fluka) as internal standard. Samples were sonicated for 5 min in
12 an ice-water bath, placed at –20°C for 1h, and then centrifuged at 1100 g for 5
13 min at 3°C. The supernatants were filtered through Fluoropore PTFE membrane
14 filters (0.2 µm pore size) to separate the extract from remains of filter and cell
15 debris. Immediately prior to injection, 1000 µL of sample was mixed with 400 µL
16 of Milli-Q water in 2.0 mL amber glass sample vials, which then were placed in
17 the HPLC cooling rack (4°C). The pigment extracts were analysed using a
18 Shimadzu HPLC constituted by a solvent distributor module (LC-20AD) with a
19 control system (CBM-20A), a photodiode detector (SPDM20A) and a
20 fluorescence detector (RF-10AXL). The chromatographic separation of the
21 pigments was performed using a monomeric C8 column (SunFire; 15 cm long;
22 4.6 mm in diameter; 3.5 µm particle size) at a constant temperature of 25 °C.
23 The mobile phase (solvent) and respective gradient followed the method
24 developed by Zapata et al. (2000), discussed and optimized by Mendes et al.
25 (2007), with a flow rate of 1 ml min⁻¹, injection volume of 100 µl, and 40 min

1 runs. All the studied pigments were identified from both absorbance spectra and
2 retention times, and the concentrations were calculated from the signals in the
3 photodiode array detector in comparison with commercial standards obtained
4 from DHI (Institute for Water and Environment, Denmark). The peaks were
5 integrated using LC-Solution software, and all of the peak integrations were
6 checked manually and corrected when necessary. A quality assurance (QA)
7 threshold procedure, through application of quantification limit (LOQ) and
8 detection limit (LOD), was applied to the pigment data as described by Hooker
9 et al. (2005) to reduce the uncertainty of pigments found in low concentrations.
10 The LOQ and LOD procedures were performed according to Mendes et al.
11 (2007). In order to correct for losses and volume changes, the concentrations of
12 the pigments were normalized to the internal standard.

13

14 2.7. CHEMTAX analysis of pigment data

15 The relative contribution of microalgal groups to the overall biomass was
16 calculated from the class-specific accessory pigments and total chlorophyll *a*
17 (Chl *a*) using CHEMTAX v1.95 chemical taxonomy software (Mackey et al.
18 1996). CHEMTAX uses a factor analysis and steepest descent algorithm to best
19 fit the data onto an initial matrix of pigment ratios (the ratios between the
20 respective accessory pigments and Chl *a*). The procedures and calculations are
21 fully described in Mackey et al. (1996).

22 Seven taxa were selected for CHEMTAX analysis, based on identified
23 diagnostic pigments and previous experience in the region (Mendes et al.,
24 2012; 2013; 2017). Two types of diatoms were defined: Type A, containing
25 typical diatom pigmentation (chlorophylls c_1 , c_2 , fucoxanthin, diadinoxanthin),

1 and Type B, where chlorophyll c_3 replaces chlorophyll c_1 (typified by
2 *Pseudonitzschia* sp., which were commonly observed in these samples). Two
3 types of dinoflagellates were also defined: Type A, containing peridinin
4 (unambiguous marker), and Type B, containing gyroxanthin esters and
5 fucoxanthin derivatives (the latter type was associated with high densities of
6 small *Gymnodinium* sp. < 20 μ m, which is known to contain carotenoids other
7 than peridinin). Categorisation of taxa containing fucoxanthin (Fuco), 19'-
8 hexanoyloxyfucoxanthin (Hex-Fuco), and 19'-butanoyloxyfucoxanthin (But-
9 Fuco) was somewhat problematic due to the multiple possibilities (eight types of
10 haptophytes, chrysophytes, including Parmales, and some dinoflagellates –
11 Zapata et al., 2004; Wright and Jeffrey, 2006), coupled with the inability to
12 identify many of the taxa containing such pigments by light microscopy. After
13 several trials of different models and a comprehensive analysis, we have
14 included one type of haptophyte (representing Haptophyte type 8 – mainly
15 *Phaeocystis antarctica* –, as defined by Zapata et al., 2004), as well as a
16 category of Hex-fuco-containing dinoflagellates (Gall et al., 2001; Carreto et al.,
17 2001), as stated above. Cryptophytes and “green flagellates” were recognized
18 by the unambiguous markers alloxanthin and chlorophyll *b*, respectively. The
19 microscopy cell number data supported most of these groupings (see Fig. S1 in
20 Supplementary material). However, some groups, containing only few
21 specimens, were not discriminated in the microscopy among small flagellates
22 and, therefore, no comparisons are available with the CHEMTAX approach. All
23 methods and procedures for cell counts and microscopic identification are
24 detailed in Mendes et al. (2012). The microscopy data were used in this study
25 just to validate the CHEMTAX results.

1 The initial pigment ratios of major algal classes used here were compiled
2 from Higgins et al. (2011), with chemotaxonomic groups being identified
3 according to Jeffrey et al. (2011) (see Table 1(a)). The same initial ratios were
4 used in data from both study years, but data from each cruise were run
5 separately in order to detect potential variations in optimization of CHEMTAX
6 procedures. In order to account for pigment ratios' variation with irradiance
7 and/or nutrient availability, data from each cruise were also split into three bins
8 according to sample depth (0–25 m, 25–50 m and > 50 m). A series of 60
9 pigment ratio matrices were generated by multiplying each ratio from the initial
10 matrix by a random function to optimize the matrix, and 10% (n=6) of the
11 generated ratios with lowest root-mean-square residual were averaged [see
12 Wright et al. (2009) for further procedure details]. The optimized pigment ratio
13 matrix derived from CHEMTAX for the 0–25 m is presented in Table 1(b) and
14 1(c) (data from 2013 to 2014, respectively).

15

16 2.8. Photo-pigment indices

17 Photo-pigment indices were derived to assess the contribution of
18 chlorophylls and carotenoids to the total pigment (TP) pool. The chlorophylls
19 were partitioned into chlorophyll *a* (Chl*a*) and the sum of chlorophyll *b* and all
20 chlorophylls *c* (Chl*bc*). The carotenoids were separated into photosynthetic
21 carotenoids (PSC) and photoprotective carotenoids (PPC). In this study, the
22 PSC included 19'-butanoyloxyfucoxanthin, 19'-hexanoyloxyfucoxanthin,
23 fucoxanthin and peridinin, while the PPC were composed by alloxanthin,
24 diadinoxanthin, diatoxanthin, β,β -carotene and β,ϵ -carotene. Four photo-
25 pigment indices were derived and used here following Barlow et al. (2004):

1 Chl a_{TP} (chlorophyll *a* to total pigments), Chl bc_{TP} (chlorophyll *b* and chlorophylls
2 *c* to total pigments), PSC $_{TP}$ (photosynthetic carotenoids to total pigments) and
3 PPC $_{TP}$ (photoprotective carotenoids to total pigments). These indices were used
4 to investigate phytoplankton pigment acclimations in response to different
5 environmental light regimes.

6

7 2.9. Statistical analysis

8 Relationships between biomass of phytoplankton groups and
9 environmental variables at surface (first CTD sampling depth, 5-10 m; except
10 for determining water column structure, where data from the upper 100 m were
11 used) were explored by Canonical Correspondence Analysis (CCA; Ter Braak
12 and Prentice, 1988) using CANOCO for Windows 4.5 software. This analysis
13 was performed in order to identify the main patterns of the phytoplankton
14 community structure with respect to environmental variables. Biotic variables
15 were represented by the CHEMTAX-derived taxonomical groups' biomass (mg
16 m⁻³ of Chl *a*). Environmental variables included water column stability (Stability),
17 upper mixed layer depth (UMLD), meltwater percentage (MW%), sea surface
18 temperature (T), sea surface salinity (Salinity), dissolved inorganic nitrogen
19 (DIN), phosphate and silicic acid. All variables were log-transformed before
20 analysis to reduce the influence of different scales in the data sets. Monte-Carlo
21 tests were run based on 499 permutations under a reduced model ($p < 0.05$) in
22 order to evaluate the significance of the CCA.

23

24 3. Results

25

1 3.1. Environmental setting

2 The physical-chemical properties in 2013, due to the presence of sea ice,
3 showed great spatial variability throughout the study area (Fig. 2); while in 2014
4 (no sea ice) a relative homogeneity of the hydrographic properties was
5 observed. However, in this second year it was possible to observe a typical
6 north-south surface temperature gradient (Fig. 2e), which was relatively masked
7 in 2013 (Fig. 2b) by the effect of the sea ice melting. In order to better evaluate
8 the effect of sea ice on the phytoplankton communities, the sampling stations in
9 2013 were split, according to the meltwater (MW) percentage, into two data
10 sets: (i) stations under a greater influence of sea ice melting ($>2.25\%$ of MW)
11 and (ii) stations further away from this influence ($<2.25\%$ of MW) (Fig. 2c). The
12 stations sampled during 2014 showed lower and more homogeneous values of
13 meltwater percentage ($1.21 \pm 0.25\%$ MW; Fig. 2f), always lower than this
14 threshold, and were considered as a third data set.

15 The mean sea surface temperature showed noticeable differences
16 among data sets, with higher values registered in 2014 (0.31 ± 0.58 °C) and
17 much lower near the sea ice boundary in 2013 (-0.90 ± 0.24 °C; Table 2). Mean
18 sea surface salinity showed a similar pattern, i.e., lower values (33.68 ± 0.09)
19 near the sea ice boundary in 2013; intermediate values (33.98 ± 0.04) at
20 stations with lower MW% during 2013; and highest surface salinity values in
21 2014 (34.14 ± 0.07 ; Table 2). The low salinities observed at stations with higher
22 MW% (>2.25) in 2013 led to a significant increase in water column stability,
23 accompanied by shallower UMLD (see Table 2). Relatively deep mixed layers,
24 with an average depth around 50 m, were recorded in 2014.

1 The surface nutrient concentrations, during both sampling periods, were
2 relatively high throughout the study area (Table 2). However, there was
3 considerable variability, mainly in the silicic acid concentrations, whose average
4 values were substantially lower during 2014 (Table 2), when diatoms
5 contributions were much higher (see Fig. 3c).

6

7 3.2. Phytoplankton biomass and community composition

8 During the study period, surface Chl *a* concentration ranged between
9 0.27 and 2.15 mg m⁻³ (Table 2). Higher mean surface Chl *a* concentrations
10 (1.37 ± 0.35 mg m⁻³) were recorded in 2013 at stations with lower MW% values,
11 i.e., in the northern area, farther from the sea ice boundary (see Fig. S2 in the
12 Supplementary material).

13 The main phytoplankton groups in the region during 2013 were
14 cryptophytes, dinoflagellates type B (represented mainly by the genus
15 *Gymnodinium*; see Fig. S1 in the Supplementary material) and the haptophyte
16 *P. antarctica*, contributing, altogether with more than 75% of the total Chl *a*, on
17 average (Fig. 3). Although those three groups together comprised most of the
18 biomass in the region during 2013, cryptophytes were the dominant group at
19 stations with higher MW% values (Fig. 3a); while dinoflagellates type B
20 dominated the stations with lowest influence of sea ice melting (Fig. 3b).
21 Overall, cryptophytes were replaced by diatoms type B (represented mainly by
22 the genus *Pseudonitzschia*; see Fig. S1 in the Supplementary material) in 2014
23 (Fig. 3c). The spatial distribution of relative contributions of the main
24 phytoplankton groups to total Chl *a* in surface waters, derived from CHEMTAX,
25 are shown in Figs. S2 and S3 (see Supplementary material).

1 Vertical distributions of the phytoplankton groups (contribution to Chl *a*)
2 for a transect along a gradient, from open water to the sea ice edge, are shown
3 in 2013 (Fig. 4). As shown in Fig. 4, in 2013, the thickness of the low-salinity
4 layer increased with proximity to the ice-edge, as a result of fresh water input
5 from sea ice melting (higher values of MW%). On the other hand, the density
6 profiles show that the UMLD (stratification) decreased (increased), respectively,
7 toward the sea ice edge and was influenced primarily by an increasingly thick
8 layer of fresher water. The phytoplankton community composition displayed an
9 orderly succession along this gradient (see Fig. 4): Dinoflagellates type B were
10 dominant at open-water stations (Sts. 21 and 20), accompanied by a significant
11 contribution of diatoms type B, mainly at St. 21, and were gradually replaced by
12 cryptophytes at stations closer to the sea ice boundary. In addition,
13 cryptophytes were conspicuously found in shallow upper mixed layers (0–25 m),
14 above the pycnocline, at stations under well-stratified conditions. The lowest
15 phytoplankton biomass, as indicated by Chl *a* values, were recorded at two
16 stations closest to the sea ice edge.

17 The 2014 transect showed an extremely different pattern from that
18 observed in 2013 (see Fig. 5). Increased water column stratification,
19 accompanied by the establishment of a deeper mixed layer, was generally
20 observed from northern to southern stations (Fig. 5). A north-south gradient was
21 also observed for both overall phytoplankton biomass and the relative
22 distribution of taxonomic groups, with higher Chl *a* concentration at the southern
23 stations and decreasing northwards. The highest biomass levels within the UML
24 were generally characterized by a major contribution of dinoflagellates and

1 diatoms (both type B). Cryptophytes, moderately abundant in the surface layers
2 (0–25 m), were always below 15% of the total Chl *a*.

3

4 3.3. Photo-pigment indices

5 There was a concomitant variability in photo-pigment indices with
6 changes in dominance of key phytoplankton groups across the study region
7 (Fig. 6). The Chl_{aTP} index varied between 0.4 and 0.6, with highest values found
8 in the surface layers (Fig. 7a) and associated with a cryptophytes-dominated
9 community (Fig. 6a). Similarly to Chl_{aTP} , the PPC_{TP} at the surface increased
10 following the higher proportion of cryptophytes (Fig. 6a). In contrast, increases
11 in surface PSC_{TP} were associated with higher proportions of dinoflagellates type
12 B (Fig. 6b), declining to values ~ 0.1 in samples with dominance of cryptophytes.
13 The photo-pigment indices in deeper waters, i.e., below the UMLD, were
14 generally constant, and no particular trend was associated with any
15 phytoplankton group (Fig. 7). It is also noteworthy that the PSC_{TP} was generally
16 greater in deep than in surface layers, while PPC_{TP} was higher at the surface,
17 especially in regions with a clear dominance of cryptophytes, where PPC_{TP}
18 exceed PSC_{TP} (Fig. 7a). Chl_{bcTP} was relatively constant throughout the study
19 area and at collected depths, ranging between 0.1 and 0.2 (see Figs. 6 and 7).

20

21 3.4. Phytoplankton response to environmental drivers

22 A Canonical Correspondence Analysis (CCA) was used to investigate the
23 response of the phytoplankton community (derived from CHEMTAX) to the
24 environmental variables observed in this study (Fig. 8). The relationships

1 showed that the nine selected variables significantly contributed ($p < 0.01$) to
2 explain the spatial distribution of phytoplankton groups. The multivariate
3 analysis showed a strong association between phytoplankton groups and
4 seawater physical and chemical properties. By using all data from both cruises
5 (Fig. 8a), the CCA explained 93.9% of the variance associated with the
6 phytoplankton–environment relationship. The first canonical root, explaining
7 almost all the phytoplankton variation (74.1%), revealed a notable separation
8 between 2013 (circles in Fig. 8) and 2014 (triangles in Fig. 8a) stations.
9 Cryptophytes, which were dominant in 2013, were found to be strongly
10 associated with high values of MW%, stability, silicic acid and phosphate
11 concentrations, and negatively associated with UMLD, salinity and temperature.
12 Diatoms type B and dinoflagellates type A, particularly associated with 2014
13 conditions, showed an opposite trend with respect to these environmental
14 variables, being strongly associated with high salinity, UMLD, and temperature,
15 and negatively associated with MW% and stability. The dinoflagellates type B
16 and *P. antarctica*, two important and representative groups in both years, were
17 associated with intermediate values of most variables, such as stability, salinity,
18 MW% and UMLD.

19 A Canonical Correspondence Analysis (CCA) was also used to
20 investigate the response of the phytoplankton groups to the environmental
21 variables using only data from 2013 (Fig. 8b). In this case, the CCA explained
22 95.9% of the variance associated with the phytoplankton–environment
23 relationship. The first canonical axis alone explained 88.1% of the variance. The
24 diatoms type B were found to be strongly associated with high values of
25 temperature and salinity, and negatively associated with stability and MW%. It is

1 worth noting that at the stations with higher values of MW% (near the sea ice
2 edge; yellow circles in Fig. 8b) a gradient as a function of the UMLD was
3 observed. Dinoflagellates type B were positively associated with the UMLD,
4 while cryptophytes were found to be associated with low values of UMLD (also
5 illustrated in Fig. 9a). Consequently, an increased contribution of cryptophytes
6 over dinoflagellates type B was observed at stations with shallower UMLD (see
7 Fig. 9b).

8

9 **4. Discussion**

10 The geographical setting of this study is the vicinity of the Weddell-Scotia
11 Confluence (WSC) at the northwestern Weddell Sea. This region is one of the
12 few areas in the Southern Ocean where the open ocean, seasonal sea ice and
13 permanent pack ice occur altogether, reflecting the complex patterns of water
14 circulation and the annual cycle of sea-ice formation and ablation (Hofmann et
15 al., 1996; Hewitt, 1997). The annual cycle of sea ice extent in the region is
16 marked by a minimum in February, and most of the sea ice remaining until
17 summer is found eastward of the Antarctic Peninsula (Cavalieri and Parkinson,
18 2008). However, there is considerable interannual variability on the sea ice
19 extent associated with the meteorological and oceanographic conditions around
20 the continent (Turner et al., 2013).

21 In general, the WSC is characterized by a mixture of surface/intermediate
22 waters between the warm water masses (temperature higher than 0°C)
23 originated in the Weddell and Scotia seas, and cold (less than 0°C), fresher
24 waters from the continental shelves of the tip of the Antarctic Peninsula
25 (Patterson and Sievers, 1980). The region is also characterized by generally

1 weak water column stratification, being one of the main deep passages allowing
2 Weddell Sea deep waters to be exported (Franco et al., 2007; Ferreira and
3 Kerr, 2017), and vulnerable to the displacement of the Antarctic Circumpolar
4 Current fronts (Patterson and Sievers, 1980; Orsi et al., 1995).

5 The upper water column within the WSC is characterized by the Antarctic
6 Surface Water (AASW), which displays a wide range of both temperature and
7 salinity, located southward of the Polar Front. The western WSC is also
8 characterized by high nutrient concentrations, reflecting the influence of the
9 nutrient-rich surface Weddell Sea shelf waters (Holm-Hansen et al., 1997).
10 Those water masses flow along the continental slope driven by the Antarctic
11 Slope Front (ASF) towards the southern Scotia Sea (Heywood et al., 2004;
12 Thompson et al., 2009) and this flow is considered a key factor for the
13 enhancement of surface chlorophyll levels in the region (Thompson and
14 Youngs, 2013). In fact, dissolved macronutrient concentrations at surface,
15 during both sampling periods in this work (see Table 2), were high and unlikely
16 to have limited phytoplankton growth, indicating that other processes were
17 driving the patchy distribution of phytoplankton biomass (Chl *a*) and composition
18 over the study area. In open waters of the Southern Ocean, high nutrient and
19 low chlorophyll (HNLC) conditions prevail in most areas, due to iron scarcity (De
20 Baar et al., 2005; Jickells et al., 2005), elevated grazing (Burkill et al., 1995),
21 and/or light limitation (Smith et al., 2000; van Oijen et al., 2004), where
22 chlorophyll concentrations are consistently below 0.5 mg m^{-3} and phytoplankton
23 are frequently characterized by small motile organisms (Morel et al., 1991;
24 Smith and Lancelot, 2004; Thomson et al., 2010). Although in our study region
25 Chl *a* concentrations have almost always exceeded this value (mean around 1

1 mg m⁻³), indicating some degree of iron supply, the phytoplankton communities
2 were massively dominated by nanoflagellates, including cryptophytes, small
3 dinoflagellates and *Phaeocystis antarctica* (more than 75% of total Chl *a*) – a
4 typical HNLC phytoplankton assemblage.

5 Our samplings took place during the late summer, when the existing
6 phytoplankton community results from the succession associated with timing
7 and extent of ice melting during the summer (e.g., Moline and Prézelin 1996;
8 Garibotti et al., 2005). Diatom blooms are generally observed in early summer,
9 under sea ice retreating process. Later, flagellate blooms, such as cryptophytes,
10 replace diatoms (Ducklow et al. 2007). In a final succession stage, the
11 community is dominated by diatoms and other unidentified phytoflagellates
12 (Moline and Prézelin 1996; Garibotti et al. 2005). Although in the present study
13 a seasonal variation was not evaluated, the distinct conditions
14 (presence/absence of sea ice) observed between both years adds a different
15 perspective to phytoplankton community dynamics in the NAP, providing an
16 ideal scenario for studying changes and adaptations of phytoplankton
17 communities to distinct environmental conditions.

18 The two contrasting summer conditions, 2013 strongly influenced by the
19 presence of sea ice, and 2014 with practically no sea ice melting condition,
20 reflected in the water physical-chemical properties. In the first year, a great
21 spatial variability was recorded throughout the study area, while in the second a
22 relative homogeneity in the hydrographic properties was observed. The low
23 surface water salinities at stations near the sea ice boundary in 2013 led to a
24 significant increase in water column stability, accompanied by shallower UMLD.

1 The phytoplankton community composition displayed a straight succession
2 pattern along this environmental gradient: dinoflagellates type B were dominant
3 at stations with less influence of meltwater and were gradually replaced by
4 cryptophytes at stations closer to the sea ice boundary (see Fig. 4). Even within
5 stations with higher contributions of meltwater (near the sea ice edge) it was
6 possible to observe a gradient as a function of the UMLD, i.e., dinoflagellates
7 type B positively associated with deeper UMLD, and cryptophytes associated
8 with shallower UMLD (see Fig. 9). Therefore, an increased contribution of
9 cryptophytes over dinoflagellates type B was observed at stations with
10 shallower (0-25 m) UMLD, under stratified conditions, above the pycnocline,
11 although with lower biomass (chlorophyll *a*) close to the sea ice edge, probably
12 as a result of melt water dilution processes.

13 Several studies have highlighted the increasing importance of
14 cryptophytes in coastal regions of the AP, especially in shallower mixed layers
15 and lower chlorophyll *a* in summer, associated with lower diatom abundances
16 (Mendes et al., 2013; Rozema et al., 2017; Schofield et al., 2017). Shifts from
17 diatoms to cryptophytes dominance have been previously attributed to
18 sedimentation of large diatoms (Castro et al., 2002), advection (Moline and
19 Prézelin, 1996), grazing (Garibotti et al., 2003), iron availability (Mendes et al.,
20 2013), and preference/physiological tolerance of cryptophytes to lower salinity
21 waters (Moline et al., 2004). Cryptophytes in Antarctic coastal waters are often
22 confined to surface layers that are highly exposed to potentially inhibiting
23 irradiance and yet they appear to thrive. The association of this group with high
24 light exposure has been recently explored (Mendes et al. 2017, this issue). It

1 was suggested that the gradual dominance of cryptophytes in coastal waters of
2 the AP in strongly stratified and shallow mixing surface layers is associated with
3 their pigment protection capability. In the present study, in a relatively open
4 ocean area, cryptophytes followed the same pattern, suggesting that even in
5 offshore regions of the NAP, where the conditions favour the development of a
6 shallow upper mixed layer and strong water column stratification, e.g. by the
7 effect of sea ice melting, they can emerge as an important component of the
8 algal communities. The dominance of cryptophytes, in place of other groups,
9 such as diatoms, may influence the trophic webs in the region, as cryptophytes
10 are more efficiently grazed by salps than by Antarctic krill (Moline et al., 2004),
11 threatening the long-term viability of krill-dependent species (e.g. Seyboth et al.,
12 2016).

13 In opposition to the distribution of cryptophytes, the dinoflagellates type B
14 (mainly small *Gymnodinium* spp. < 20 µm) were positively associated with
15 UMLD (see Figs. 8 and 9) indicating an adaptation/preference to deeper mixed
16 layers. The occurrence and dominance of dinoflagellates type B, especially
17 *Gymnodinium* spp., is of particular interest because they include toxic species
18 adapted to disperse in coastal currents and frontal systems (Smayda, 2002).
19 Although autotrophic dinoflagellates (*Gymnodinium* spp.) have already been
20 reported as important contributors to total Chl *a* biomass in some well-stratified
21 Antarctic waters (Savidge et al., 1995; Kang et al., 2001; Mendes et al., 2012,
22 2013), an ecological approach to explain the distribution patterns of this group
23 in Antarctic environments has not yet been explicitly addressed. In this study,
24 there were apparently opposing environmental conditions, favourable to either

1 those dinoflagellates or cryptophytes, as suggested in Fig. 9 (under contrasting
2 UMLD) and also in Fig. S2. Therefore, an apparent complementary spatial
3 distribution is seen between those two groups suggesting different niche
4 adaptations. In this context, a finer taxonomic identification of both gymnodinoid
5 dinoflagellate species and cryptophytes is needed in the NAP region. Difficulties
6 in identifying those groups in light microscopy of preserved samples could be
7 overcome by the analysis of living cells and their molecular structure
8 (Hoppenrath et al., 2009).

9 In this work, similarly to that proposed by Mendes et al. (2017, this
10 issue), we hypothesize that cryptophytes would bear photophysiological
11 plasticity to tolerate high irradiances in the upper layers of the Antarctic waters
12 in summer and thrive under such conditions. The relative replacement of major
13 phytoplankton groups across the study area resulted in changes in pigment
14 composition, as reflected by the photo-pigment indices (as illustrated in Figs. 6
15 and 7). These proportions are similar to those in Mendes et al. (2017, this issue)
16 for the Gerlache Strait – a coastal region of the NAP where cryptophytes have
17 been shown to dominate – with the ratios of photoprotective carotenoids to total
18 pigments (PPC_{TP}) increasing concomitantly with an increase in the proportion of
19 cryptophytes (Fig. 6a). Although this group do not possess a xanthophyll cycle,
20 they are able to induce synthesis of the photoprotective carotenoid alloxanthin
21 under light stress, presumably enhancing non-photochemical quenching (NPQ)
22 capacity (discussed in detail by Mendes et al. 2017, this issue). Similar
23 physiological adaptations to irradiance, i.e., an increase in photoprotective
24 pigments content, have been previously reported in Ross Sea phytoplankton

1 assemblages (e.g. Arrigo et al., 2010; Tozzi and Smith, 2017), suggesting that
2 light is a major factor in shaping phytoplankton communities in the region. In
3 contrast, the photosynthetic carotenoids (PSC) were more prominent at
4 dinoflagellate-dominated stations (Figs. 6b and 7b), mainly driven by high
5 concentration of fucoxanthin and its derivatives. Photosynthetic carotenoids
6 have a significant role in extending the phytoplankton light-harvesting spectrum,
7 thus ensuring optimal absorption efficiencies (Kirk, 2011). Therefore, it appears
8 that the dinoflagellates were not subjected to excess irradiance physiological
9 stress, probably by being associated with generally deeper UMLD conditions,
10 leading to shorter time exposure to light inhibiting levels.

11 Although our results indicate an optimization of light-protection capability
12 of cryptophytes for prevailing in the highly illuminated shallower mixed layers,
13 other factors such as adaptability to iron limiting conditions and/or mechanisms
14 for alleviation micro-zooplankton grazing cannot be discarded as possible
15 causes for the success of cryptophytes in the NAP surface waters.

16

17 **5. Concluding remarks**

18 Stratification is a primary condition for seasonal development of algal
19 blooms (e.g. Margalef et al., 1979), mainly after a turbulent condition, as it
20 creates a stable surface layer that allows for the maintenance of phytoplankton
21 in a favourable light regime. In our study area, stratification (causing water
22 column stability) induced by meltwater coupled with the depth of the mixing
23 layer seem to be the most important factors influencing the phytoplankton
24 community composition and spatial distribution. Contrasting water column

1 conditions, particularly in 2013, determined the dominance of either
2 cryptophytes confined to shallow surface layers, with apparently efficient photo-
3 protection traits or dinoflagellates under less light stress in deeper surface
4 mixing layers. In 2014, under no ice conditions, diatoms replaced cryptophytes,
5 but dinoflagellates were again a very important group. Other biological
6 adaptations such as iron stress tolerance or grazing avoidance mechanisms
7 may also play a role in the structuring of phytoplankton communities in the NAP.
8 Understanding the physical regulation and biological traits and adaptations of
9 phytoplankton communities along the NAP is critical to understanding the
10 regional ecology and biogeochemistry. Such phytoplankton monitoring
11 procedures are vital to fully understand the function of marine food webs,
12 particularly in regions extremely sensitive to global climate change, as the NAP
13 region.

14

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3

4 **Figure captions**

5

6 **Figure 1:** Study area and stations' locations during 2013 and 2014 summer
7 cruises. The solid white line represents the sea ice boundary in 2013. The
8 bathymetry is represented by the color scale bar on the right. An inset map in
9 the upper left corner shows a larger area that pinpoints where the main map is
10 located.

11

12 **Figure 2:** Surface distributions of salinity (a, d), temperature (b, e) and
13 meltwater percentage (c, f) in 2013 (a–c) and 2014 (d–f). The dashed white line
14 in (c) represents a meltwater contribution of 2.25%. Black dots represent
15 stations' location.

16

17 **Figure 3:** Surface averages of relative contribution of phytoplankton groups
18 (CHEMTAX-allocated) to total chlorophyll *a* at (a) stations under a greater
19 influence of sea ice melting (>2.25% of MW) in 2013; (b) stations further away
20 from influence of sea ice melting (<2.25% of MW) in 2013; and (c) stations
21 sampled in 2014.

22

23 **Figure 4:** Vertical profiles of water column salinity, temperature, density and
24 fluorescence (top panel), and depth distribution of phytoplankton groups'
25 biomass (as chlorophyll *a* concentration) calculated by CHEMTAX (bottom
26 panel) along a north-south transect, from open water to the sea ice edge, in
27 2013 (see inset map on the top right).

28

29 **Figure 5:** Vertical profiles of water column salinity, temperature, density and
30 fluorescence (top panel), and depth distribution of phytoplankton groups'
31 biomass (as chlorophyll *a* concentration) calculated by CHEMTAX (bottom
32 panel) along the same north-south transect shown in Fig. 4, but for 2014
33 condition, i.e., no detected sea ice (see inset map on the top right).

1

2 **Figure 6:** Relationships between photo-pigment indices and proportions of (a)
3 cryptophytes and (b) dinoflagellates type B. Chl_{aTP} =total chlorophyll *a*/total
4 pigments; PSC_{TP} =photosynthetic carotenoids/total pigments; Chl_{bcTP} =sum of
5 chlorophyll *b* and *c*/total pigments; PPC_{TP} =photoprotective carotenoids/total
6 pigments. See text for more details.

7

8 **Figure 7:** Vertical profiles of photo-pigment indices at the (a) four selected
9 cryptophytes-dominated (> 60% of total Chl *a*) stations (St. 11, 12, 16 and 17)
10 and (b) four selected dinoflagellates type B-dominated (>55% of total Chl *a*)
11 stations (St. 7, 8, 21 and 30). The density profiles of each station (gray
12 continuous lines), with the respective mean value of the UMLD (gray horizontal
13 dashed lines), are also shown. Chl_{aTP} =total chlorophyll *a*/total pigments;
14 PSC_{TP} =photosynthetic carotenoids/total pigments; Chl_{bcTP} =sum of chlorophyll *b*
15 and *c*/total pigments; PPC_{TP} =photoprotective carotenoids/total pigments. See
16 text for more details and Fig. 1 for stations' locations.

17

18 **Figure 8:** Canonical Correspondence Analysis ordination diagram of absolute
19 contributions of different phytoplankton groups at sea surface (a) using all data
20 from both cruises and (b) using only data from 2013. The first two ordination
21 axes represented 50.2 and 68.6% (all data and only 2013 data, respectively) of
22 the total phytoplankton variance, and 91.2 and 95.9%, respectively, of the
23 phytoplankton–environment relationships. Arrows indicate explanatory variables
24 [water column stability (Stability), upper mixed layer depth (UMLD), and sea
25 surface temperature (T), salinity (Salinity), chlorophyll *a* (Chl *a*), meltwater
26 percentage (%MW) and dissolved inorganic nitrogen (DIN), phosphate (PO₄)
27 and silicic acid (SiO₂)]. Blue crosses refer to absolute contributions of
28 phytoplankton groups. Crypto = cryptophytes; Dino-A = dinoflagellates type A;
29 Dino-B = dinoflagellates type B; Diat-A = diatoms type A; Diat-B = diatoms type
30 B; P. ant. = *Phaeocystis antarctica*; G. flag. = green flagellates. Symbols and
31 colors represent stations from different data sets (yellow circles = 2013 stations
32 with MW >2.25%; blue circles = 2013 stations with MW <2.25%; red triangles =
33 2014 stations). Stations 16 and 30 in (b), both in 2013, are labeled because

1 they represent very distinct environmental and biological conditions and their
2 vertical density profiles and phytoplankton composition are shown in Fig. 7b.

3

4 **Figure 9:** (a) Relationship between surface contributions of cryptophytes and
5 dinoflagellates type B at stations under a great influence of sea ice melting
6 (>2.25% of MW) during 2013 ($r^2 = 0.92$; $p < 0.001$). Inset: relationship between
7 upper mixed layer depth (UMLD) and surface proportions of cryptophytes (red
8 circles; $r^2 = 0.58$; $p < 0.001$) and dinoflagellates type B (blue circles; $r^2 = 0.67$;
9 $p < 0.001$) at stations under a great influence of sea ice melting (>2.25% of MW)
10 during 2013. (b) Vertical profiles of density at the two selected stations (see Fig.
11 6b) under a great influence of sea ice melting during 2013, and respective
12 relative contribution of taxonomic groups in the upper mixed layer. See Fig. 3
13 for color representations of different phytoplankton groups in the pie charts.
14 Crypto = cryptophytes; Dino-B = dinoflagellates type B.

15

Table 1: Pigment to chlorophyll *a* ratios used for CHEMTAX analysis. Initial ratios before analysis (a); 2013 optimized ratios (for 0–25 m bin) after analysis (b); and 2014 optimized ratios (for 0–25 m bin) after analysis (c). Chl *c*₃ = chlorophyll *c*₃; Chl *c*₁ = chlorophyll *c*₁; Perid = peridinin; But-Fuco = 19'-butanoyloxyfucoxanthin; Fuco = fucoxanthin; Hex-Fuco = 19'-hexanoyloxyfucoxanthin; Hex-kfuco = 19'-hexanoyloxy-4-ketofucoxanthin; MGDG-Chl *c*₂ = Chl *c*₂-monogalactosyldiacylglycerol ester; Gyro-e = gyroxanthin diester; Allo = alloxanthin; Chl *b* = chlorophyll *b*; Chl *a* = chlorophyll *a*.

| | Chl <i>c</i> ₃ | Chl <i>c</i> ₁ | Perid | But-Fuco | Fuco | Hex-Fuco | Hex-kfuco | MGDG-Chl <i>c</i> ₂ [18/14] | MGDG-Chl <i>c</i> ₂ [14/14] | Gyro-e | Allo | Chl <i>b</i> | Chl <i>a</i> |
|---|---------------------------|---------------------------|-------|----------|-------|----------|-----------|--|--|--------|-------|--------------|--------------|
| (a) Input matrix | | | | | | | | | | | | | |
| Diatoms-A | 0 | 0.087 | 0 | 0 | 0.775 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Diatoms-B | 0.083 | 0 | 0 | 0 | 0.998 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-A | 0 | 0 | 0.804 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-B | 0.205 | 0 | 0 | 0.079 | 0.219 | 0.135 | 0 | 0 | 0.005 | 0.043 | 0 | 0 | 1 |
| <i>Phaeocystis antarctica</i> | 0.118 | 0 | 0 | 0.116 | 0.185 | 0.393 | 0.036 | 0.047 | 0 | 0 | 0 | 0 | 1 |
| Cryptophytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.253 | 0 | 1 |
| Green flagellates | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.911 | 1 |
| (b) Ouput matrix: 0-25 m (2013 data) | | | | | | | | | | | | | |
| Diatoms-A | 0 | 0.084 | 0 | 0 | 1.239 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Diatoms-B | 0.174 | 0 | 0 | 0 | 1.134 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-A | 0 | 0 | 1.279 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-B | 0.145 | 0 | 0 | 0.154 | 0.232 | 0.059 | 0 | 0 | 0.034 | 0.009 | 0 | 0 | 1 |
| <i>Phaeocystis antarctica</i> | 0.177 | 0 | 0 | 0.068 | 0.244 | 0.556 | 0.025 | 0.071 | 0 | 0 | 0 | 0 | 1 |
| Cryptophytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.360 | 0 | 1 |
| Greenflagellates | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.284 | 1 |
| (c) Ouput matrix: 0-25 m (2014 data) | | | | | | | | | | | | | |
| Diatoms-A | 0 | 0.128 | 0 | 0 | 0.912 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Diatoms-B | 0.073 | 0 | 0 | 0 | 0.683 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-A | 0 | 0 | 0.912 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Dinoflagellates-B | 0.138 | 0 | 0 | 0.172 | 0.387 | 0.027 | 0 | 0 | 0.012 | 0.010 | 0 | 0 | 1 |
| <i>Phaeocystis antarctica</i> | 0.341 | 0 | 0 | 0.167 | 0.299 | 0.730 | 0.017 | 0.112 | 0 | 0 | 0 | 0 | 1 |
| Cryptophytes | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.313 | 0 | 1 |
| Greenflagellates | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1.184 | 1 |

Table 2: Average, standard deviation (in parentheses), minimum and maximum (in square brackets) values of environmental properties at surface (except UMLD and Stability) for the three data sets considered in this study: (i) stations under a greater influence of sea ice melting (>2.25% of MW) in 2013; (ii) stations further away from influence of sea ice melting (<2.25% of MW) in 2013; and (iii) stations sampled in 2014. % MW = meltwater percentage; UMLD = upper mixed layer depth; DIN = dissolved inorganic nitrogen.

| Environmental variables | 2013 (n=18) >2.25% MW | 2013 (n=15) <2.25% MW | 2014 (n=13) |
|--|-------------------------------------|-------------------------------------|--------------------------------|
| % MW | 2.99 (0.34) [2.31; 3.47] | 1.99 (0.17) [1.61; 2.24] | 1.21 (0.25) [0.84; 1.62] |
| Temperature (°C) | -0.90 (0.24) [-1.26; -0.30] | 0.17 (0.45) [-0.44; 1.12] | 0.31 (0.58) [-0.33; 1.32] |
| Salinity | 33.68 (0.09) [33.55; 33.89] | 33.98 (0.04) [33.93; 34.08] | 34.14 (0.07) [34.00; 34.21] |
| UMLD (m) | 24 (10) [13; 47] | 39 (19) [16; 83] | 51 (24) [18; 103] |
| Stability (10^{-6} rad ² m ⁻¹) | 4.55 (0.82) [3.26; 6.20] | 2.26 (0.58) [0.95; 3.13] | 1.55 (0.71) [0.29; 2.99] |
| DIN (μ M) | 25.94 (1.56) [22.69; 28.00] | 28.48 (3.31) [25.39; 36.24] | 27.50 (1.25) [25.06; 29.58] |
| Phosphate (μ M) | 1.92 (0.38) [1.48; 2.89] | 1.87 (0.17) [1.37; 2.05] | 1.37 (0.11) [1.15; 1.51] |
| Silicic acid (μ M) | 38.20 (3.54) [33.44; 43.90] | 42.64 (8.10) [33.15; 54.42] | 29.30 (3.78) [21.27; 34.08] |
| Chlorophyll a (mg m ⁻³) | 0.98 (0.29) [0.53; 1.63] | 1.37 (0.35) [0.82; 2.15] | 0.93 (0.42) [0.27; 1.57] |

